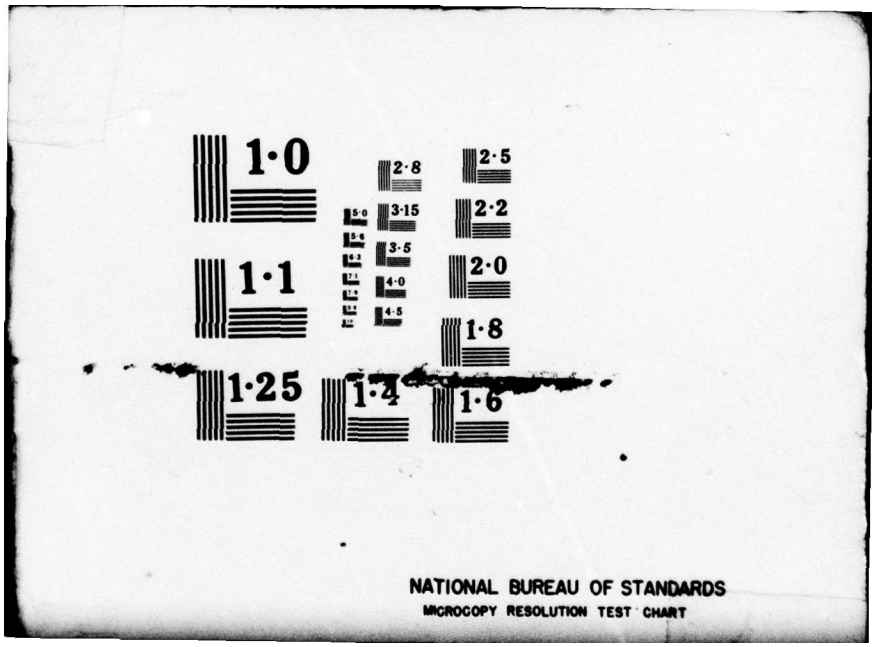
AD-A058 538 CENTER FOR NAVAL ANALYSES ARLINGTON VA F/G 9/1
TEMPERATURE AND CURRENT DEPENDENCE OF DEGRADATION IN RED-EMITTI--ETC(U)
JUN 78 J M RALSTON, J W MANN

UNCLASSIFIED CNA-PP-226 NL

1 OF 1
ADA
058538

END
DATE
FILMED
11-78
DDC


1·0
1·1
1·25
2·8
3·15
3·5
4·0
4·5
1·4
2·5
2·2
2·0
1·8
1·6
NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

AD No. ____ AD A058538
DDC FILE COPY

(2) NW

55 000226.00

(6) TEMPERATURE AND CURRENT DEPENDENCE OF DEGRADATION IN RED-EMITTING GaP LEDs.

(10) J. M. Ralston [redacted] J. W. Mann

(14) CNA-PP-226

(9) Professional Paper, No. 226

(11) June [redacted] 78

(12) 41p.

The ideas expressed in this paper are those of the author. The paper does not necessarily represent the views of the Center for Naval Analyses.

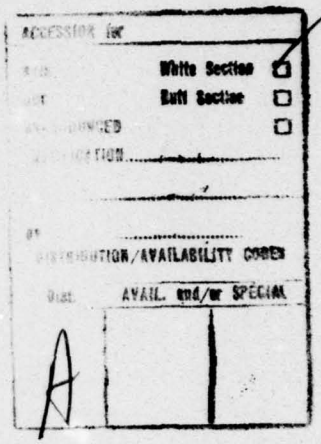
DDC
RECEIVED
SEP 13 1978
A

CENTER FOR NAVAL ANALYSES
1401 Wilson Boulevard
Arlington, Virginia 22209

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

78 09 12 024
077270

TEMPERATURE AND CURRENT DEPENDENCE OF DEGRADATION IN RED-EMITTING GaP LEDs



by

J. M. Ralston
Center for Naval Analyses
1401 Wilson Boulevard
Arlington, Va. 22209

and

J. W. Mann
Bell Telephone Laboratories, Inc.
600 Mountain Avenue
Murray Hill, N.J. 07974

ABSTRACT

Experimental studies have been performed on several aspects of the degradation of electroluminescent quantum efficiency in Zn,O-doped GaP light emitting diodes. The dependence of degradation on stress temperature, stress current (experienced during accelerated aging) and measurement current (at which quantum efficiency is evaluated) has been empirically determined from experiments on several lots of devices. It is shown that degradation is dominated by a decrease in bulk p-side radiative recombination efficiency. The degradation of other factors (such as injection efficiency and injection ratio) contributing to the overall electroluminescent efficiency has only a secondary effect. Moreover, it is shown empirically that the dependences of degradation on temperature and stress current are separable.

09 12 024

I. INTRODUCTION

In an earlier paper,[1] evidence was presented that a mode of bulk radiative efficiency degradation is operative in red-emitting LED material. This paper is concerned with characterizing the temperature and current dependence of red LED degradation. The diodes studies were fabricated from several different GaP slices: RP 55-35, RP 77-68, RP 71-38, RP 71-33, RP 71-39, RP 78-29 and RP 64-30.

In terms of degradation phenomenology, this study revealed that: 1. Degradation results primarily from a reduction in bulk radiative recombination efficiency on the p-side of the junction.[1] 2. Degradation of the net efficiency of thermally injecting minority electrons into the p-region, although sometimes appreciable, is not the dominant cause of LED failure. 3. The temperature and current dependences of degradation are separable. These observations are of considerable theoretical interest as well as a practical importance in predicting the reliability of devices incorporating these LEDs. A theoretical model of LED degradation based on early results of these experiments has been developed and presented earlier.[2]

II. EXPERIMENTAL PROCEDURES

The test devices were .015 in (0.4 mm) LED chips thermo-compression (TC) bonded p-up and hermetically sealed (in N_2-He_2 ambient) in TO-18 glass-window packages. These devices exhibited a high order of reproducibility from device to device within a given slice batch. Any diodes notably different from the mean of the set in any characteristic

were culled before experimentation began. The most frequent cause of culling was an excess of nondiffusion current components at low bias (1.4V). Diodes were also occasionally eliminated from consideration due to excessive contact resistance.

Aging studies were were most often performed at dc stress currents of 30 mA (20 A/cm^2). To obtain severe degradation within a reasonable time scale it was necessary to perform stressed aging at elevated temperatures. Obtaining data at too high a temperature, however, decreases the confidence of the results when extrapolated to practical device operating conditions. As a compromise, ambient stress temperatures of 100°C, 150°C and 200°C were chosen. The junction temperatures of the devices being stressed at 30 mA were ~20°C above ambient due to diode and header thermal resistance ($R_{\theta_{JA}} \approx 250^{\circ}$-$300^{\circ}$C/Watt).[3]

The devices tested were characterized first before degradation, again after the first hour of stress and subsequently at appropriate intervals thereafter. In most cases, this characterization consisted of measuring the external electroluminescent efficiency at (pulsed) measurement currents in the range 1-100 mA.[4] As is shown later, measurement of device efficiency over such a wide current range is necessary to an understanding of the physical processes active in degradation and their influence on overall radiative recombination efficiency. These measurements are made rapidly and accurately using automated data acquisition and computer data storage. It is important to clearly distinguish this variable pulsed measurement current, used as a probe of degraded device performance, from the constant stress current applied continuously during elevated temperature aging which controls the rate at which the physical process of degradation proceeds.

In addition to the above standard measurements of quantum efficiency, detailed measurements of diode current-voltage (I-V) and light-voltage (L-V) characteristics were made, in specific cases, during degradation to study particular aspects of the degradation process, i.e., the fact that bulk degradation exists and the influence of nondiffusion current components.

III. EXPERIMENTAL RESULTS

In figure 1 is plotted (linearly) the ratio of degraded to initial efficiency (η/η_o) as a function of time (log scale). With the exception of slice RP 64-30, these devices are well grouped at all three temperatures used for accelerated aging. Generally, for diodes stressed at 30 mA in 200°C ambient and measured at 10 mA, η/η_o is down to the range 0.70-0.75 after the first hour of aging. Among the samples studied, RP 55-35 is typical in its degradation behavior. The radically different behavior of slide RP 64-30 is an indication that its degradation causes may be different from those in general evidence.

As expected for processes which are thermally activated, degree of degradation is a monotonically increasing function of temperature, illustrated in figure 2. These data are shown on a scale of log η/η_o vs. root time stressed. Eckton[5] has shown that this scale often has the effect of linearizing at least a portion of the degradation curve. Such linear regions, which may be used to define time constants, τ , are indicated in the figure. Also obtainable from such plots are the mean times to failure (MTTF) at the stated temperatures, defined to

be the time such that the group mean of $\eta/\eta_o = 0.5$. In extrapolating high temperature stressed againg data to operating conditions, under the assumption of an Arrhenius activation law, both MTTF and τ have been used, with generally consistent results. This will be treated further in section IV.

Another important aspect of the degradation process is the dependence of relative degradation on measurement current (as opposed to stress current). Figure 3 shows that η/η_o at a fixed time is a monotonically increasing function of measurement current. This effect cannot be explained by changes in injection efficiency between 2 and 100 mA (see section V) and requires a careful reconsideration of radiative recombination kinetics[2,6,7] as related to device degradation.

The effect of varying stress current at a fixed ambient temperature and fixed measurement current is shown in figure 4. As might be initially expected, increased stress current enhances the degradation process. Because of thermal dissipation in the diodes under stress, junction temperature is necessarily higher at higher stress currents. Once an activation energy is obtained for the overall degradation process, the data can be corrected for this temperature dependence. This analysis is reserved to section IV, where it will be shown that an approximate power-law relationship holds between stress current and rate of degradation.

Although measurements of the degradation of electroluminescent efficiency reflect the most serious aspect of this problem from the standpoint of device reliability, there are other electrical measurements which can yield qualitative and quantitative information on physical degradation mechanisms. The most straightforward of these is the measurement of device current and light output at fixed voltage bias.[8] Such an L-I-V plot, taken

on one typical diode, is shown in figure 5 before and after severe degradation. The light output at fixed voltage will be shown in section V to be independent of all current components except electron injection. The strong degradation in light output at fixed voltage will be shown to be unequivocal evidence that bulk radiative recombinations efficiency is being directly affected. At 1.4V the device current is virtually completely nondiffusion in origin. After degradation, on this particular device, I(1.4V) has more than doubled. Yet the total current at 1.6V, still dominated by nondiffusion components, has not signficantly increased. The current dependence of quantum efficiency, for the same diode, is shown in figure 6. The undegraded device exhibits a well-defined peak at ~3.5 mA, since injection efficiency increases with total current while bulk recombination efficiency decreases due to saturation of the radiative recombination centers. In the heavily degraded diode, such a peak is barely evident.

The time dependence of the relative light output at fixed voltage is of considerable importance, since it reflect directly the evolution of the process responsible for bulk p-side degradation. This is shown in figure 7 for the different samples under two different stress conditions. RP 55-35 and RP 78-29 were stressed at 30 mA at $T_{junc} \cong 220^{o}C$, while RP 71-39 was placed in a $250^{o}C$ ambient at zero bias. Both biased samples are reduced to $L/L_0 = 0.75$ after the first hour of stress. It will be shown that this "rapid" component of degradation is not a surface effect, but in fact represents bulk material damage. By contrast, the unbiased sample does not begin to show comparable degradation until well over 1,000 hours at $T_{junc} = 250^{o}C$ have elapsed. These data suggest that although these unbiased red LEDs do eventually exhibit measurable degradation at very high temperature, this process is strongly retarded in the absence of forward bias.

The same L-I-V measurements show the increase in nondiffusion current components as ageing progresses. Figure 8 shows the total device current (measured at 1.4V) of the same devices shown in figure 7. Here the marked difference in behavior between RP 55-35 and RP 78-29 is noteworthy. The former shows considerable fluctuation in current followed by a strong increase beginning at about 50 hours stress, while the excess current of RP 78-29 is steady, and begins to show a slow increase at about the same time. The unbiased sample, RP 71-39, stored at 250^{o}C shows no significant increase in excess current components after almost 2,000 hours. Note that over the useful life of the current-stressed devices (less than 100 hours at these temperatures) the increase in excess current is in all cases negligible.

IV. TEMPERATURE AND CURRENT DEPENDENCE OF DEGRADATION

The generally accepted purpose of performing evaluated temperature degradation studies, as described above, is to come to some reasonable estimate of the useful life of the device under its expected operating conditions. To this end, the accepted proactice has been to verify that the temperature dependence of the degradation process under a given combination of stress and measurement currents is reasonably described by Arrhenius' law:

$$t(T) = c \cdot \exp^{(E_A/kT)} . \qquad (1)$$

Here t is some suitably defined characteristic time of the degradation process at absolute temperature T, E_A is an apparent activation energy which describes the temperature dependence of degradation and c a properly dimensioned constant of proportionality. Once this law has been verified to an acceptable degree over the elevated temperature range studies, the constants c and E_A are used to extrapolate the process down to operating temperatures.

Obviously, the definition of the characteristic time used in equation 1 is a critical point. One convenient choice is the mean time to failure (MTTF): the time at which the average relative efficiency ($\langle \eta/\eta_0 \rangle$) of the sample group has dropped to a value of 0.5. Such a definition, by its very objectivity, effectively ignores all the structure observable in the time dependence of η/η_0, and heavily weighs the first measurement of device efficiency and the measurements bracketing the $\eta/\eta_0 = 0.5$ point, ignoring all others. If more than one physical process is at work in the degradation process, this definition offers no hope of distinguishing them.

An alternate definition of characteristic time takes advantage of the linear regions observed when $\log \eta/\eta_0$ is plotted as a function of $\sqrt{\text{time}}$. (Cf. figure 2). The lines defined by these linear regions do not, in general, pass through the point $\eta/\eta_0 = 1$ at $t = 0$. This offset, which varies from slice to slice, is termed the "rapid component" of degradation, as distinguished from the "long term" linear region. The squared value of the exponential root-time constant describing the linear region is denoted τ. This choice of time parameter is particularly useful, since it may be measured when a group of devices is not sufficiently degraded to allow the measurement of a MTTF.

Since the MTTF is the parameter of interest in device operating life, its use is generally preferred as long as its temperature dependence satisfies equation 1. Figure 9 compares the results of using both MTTF and τ as characteristic degradation times. The diodes studies were stressed at 30 mA and measured at both 30 and 10 mA with results as shown. The MTTF values

are much less than the corresponding values of τ . This can be partly understood by noting that (in the absence of any rapid component of degradation) if the time dependence of degradation is ideally described by

$$\eta/\eta_o = \exp(-\sqrt{t/\tau}) \qquad (2)$$

then $\eta/\eta_o = 0.5$ corresponds to $t \cong \tau/2$. The fact that MTTF (at these temperatures, at this stress current) is generally less than half the corresponding value of τ reflects the presence of the rapid component of initial decay, which influences MTTF but does not enter into the measurement of τ .

Figure 9 shows that both τ and the MTTF, as measured on RP 55-35 in these experiments, agree satisfactorily with equation 1. As expected from figure 3, both MTTF and τ are larger when η/η_o is measured at 30 mA rather than 10 mA. Although the change in E_A between the two measurement conditions is not large, E_A generally tends to be slightly smaller for higher values of measurement current.

Figures 10 and 11 are Arrhenius plots of MTTF versus junction temperature for diodes made from three slices of LED material. Figure 10 is data measured at 10 mA (where device parameters are often specified) and figure 11 is data measured at the 30 mA stress current. Both figures indicate that RP 55-35 and RP 71-38 are closely matched in failure characteristics, while RP 77-68 is measureably different. The fact that the thermal activation line of this last sample crosses those of the others may indicate the presence of a qualitatively different mechanism operative in its degradation.

The dependence of LED degradation on stress current (cf. figure 4) is a matter of considerable interest in defining practical operating limits. To determine this dependence, seven groups (10 each) of diodes from from slice RP 55-35 were put on test at different combinations of stress current and ambient temperature. These results are shown in figure 12. The amount of degradation achieved is less than 50% for the 5 mA stress sample in the 100°C oven. Consequently, in figure 12 the long-term degradation time constant, τ, has been plotted as the characteristic degradation time, rather than the MTTF. The consequences of this choice of time parameter may be inferred by reference to figure 9. That is, neglecting any initial degradation components, τ is approximately twice the expected MTTF. The values of η/η_o used to determine τ were obtained at 10 mA measurement current in all cases. Figure 12 indicates that while the overall time scale (c in equation 1) of degradation is strongly dependent on stress current, the activation energy, E_A, describing its temperature dependence, is not. As implied in the figure, an activation energy of 0.7 eV will be assumed valid for the 10 mA stressed data near 150°C. Using this value of E_A, equation 1 may be used to correct the measured characteristic degradation times to a junction temperature of 150°C. This data is plotted in figure 13, using both τ (open symbols) and MTTF (solid symbols) as characteristic degradation times. When quantum efficiency is measured at 10 mA, the characteristic degradation times (MTTF and τ) show an approximate inverse relation with stress current:

$$t = (\text{const}) \cdot I_{\text{stress}}^{-x} \qquad (3)$$

with $x = 1.13$ for MTTF and 0.83 for τ. This difference probably results from the arbitrary nature of the choices of characteristic degradation time,

since both MTTF and τ are obtained from data on the same degraded samples, which can experience only one history of damage, regardless of the method chosen to analyze it.

In practical device applications the "measurement" and "stress" LED currents are effectively the same. Figure 14 shows the dependence of MTTF on stress current when the quantum efficiency is measured at the same current at which the diodes have been stressed. This current dependence is shown for diodes placed in 150°C and 200°C ambients. An E_A of 0.7 eV has been used to correct the observed MTTF to a junction temperature of 150°C or 200°C. This current dependence is well described by $x = 0.56$ at both temperatures.

V. ANALYSIS AND DISCUSSION

In analyzing the degradation of Zn,O-doped GaP LEDs, it is useful to factor the external electroluminescent efficiency into several components:

$$\eta(I) = \eta_B \cdot f(I_e) \cdot R \cdot \eta_{inj}(I) \cdot \eta_{oc} \quad . \tag{4}$$

Here I is the total device current. η_B is the bulk electroluminescent efficiency at low-injection level and $f(I_e)$ is the factor that accounts for the saturation[6,7] of Zn,O centers at higher levels of electron diffusion current, I_e. R is the ratio of electron diffusion current, I_e , to the total diffusion current, $I_e + I_h$. $\eta_{inj}(I)$ is the ratio of total (hole and electron) diffusion current ($I_e + I_h$) to total device current, I. (Previous authors[6,7] have referred to the product $R \cdot \eta_{inj}(I)$ as "injection efficiency" but the present notation lends itself to a clearer analysis of degradation phenomena). Finally, η_{oc} is the efficiency of extracting an electroluminescent photon from the LED

chip, and should be of the order of 50%-60% (in plastic encapsulation).[9] Although any of the factors in equation 3 can contribute to device degradation, the dominant loss will be shown to be from the $\eta_B f(I_e)$ product.

The optical coupling efficiency, η_{oc}, is chiefly dependent on chip geometry, refractive index of the encapsulant, surface roughness and contact absorbance. None of these have been shown to vary with degradation.

The injection ratio, R, for abrupt p-n junctions, is given by[8]

$$R = \left(1 + \frac{D_h}{D_e} \cdot \frac{N_A}{N_D} \cdot \frac{L_e}{L_h}\right)^{-1} \qquad (5)$$

where D and L are the diffusion coefficients and diffusion lengths of minority carriers and N_A and N_D are the net acceptor and donor concentrations. Capacitance measurements after degradation reveal no detectable changes in the doping densities N_A, N_D. If the minority diffusion coefficients (or their ratio) do not vary, the injection ratio depends solely on the ratio of minority diffusion lengths.

These diffusion lengths have been measured[1] by SEM for several well-characterized typical samples (RP 55-35) after 1,500 hours of degradation at 220°C. Based on averages of ~10 measurements before and after degradation at distances of ~2 μm from the pn junction, the undegraded diodes show average diffusion lengths $\langle L_{eo} \rangle = 0.85$ μm and $\langle L_{ho} \rangle = 0.36$ μm. The degraded values are $\langle L_e \rangle = 0.42$ and $\langle L_h \rangle = 0.22$. These values may be substituted into equation 5 to obtain the injection ratios before and after degradation, R_o and R:

$$R/R_o = \frac{\left(1 + \frac{D_h}{D_e}\frac{N_A}{N_D}\frac{L_{eo}}{L_{ho}}\right)}{\left(1 + \frac{D_h}{D_e}\frac{N_A}{N_D}\frac{L_e}{L_h}\right)} = \frac{0.71}{0.67} = 1.07 \qquad (6)$$

Where values[8,10] of $N_D = 1.1E18cm^{-3}$, $N_A = 3.4E17cm^{-3}$, $D_e = 4.1cm^2/sec$ and $D_h = 2.8cm^2/sec$ have been used and assumed unchanged with degradation. The electroluminescent efficiency of the same diodes had been reduced to $\eta/\eta_o = 0.1$, measured at mA. Therefore the change in injection ratio, R, although appreciable, is not a major factor. Interestingly, it appears that injection ratio can be <u>enhanced</u> in the course of overall degradation. As discussed in reference 1, it is not possible to make diffusion length measurements in the immediate vicinity of the junction. The measurements were therefore made a distance of a few diffusion lengths from the junction.

At this point, R and η_{oc} can be fairly eliminated as major factors in LED degradation. The remaining factors are $\eta_B f(I_e)$, the modulated bulk efficiency, and η_{inj}, the ratio of diffusion to total current. It is possible to measure the low level bulk efficiency variation directly by measuring the change in light output, L, at a fixed voltage bias chosen to be low enough that series resistance effects in the LED and saturation of the Zn,O centers are negligible. Under these conditions one has

$$L = \eta_B I_e = \eta_B \frac{q\sqrt{D_e}\, n_i^2}{N_A\sqrt{\tau_e}} \exp(qV/kT), \qquad (7)$$

where n_i is the intrinsic carrier concentration, and τ_e the minority electron lifetime. It can be shown[2,11] that at low levels of electron injection the degradation of bulk efficiency η_B/η_{Bo}, equals the degradation of minority electron lifetime τ_e/τ_{eo}. One has then

$$\frac{\eta_B}{\eta_{Bo}} = \frac{\tau_e}{\tau_{eo}} \tag{8a}$$

and

$$\frac{L}{L_o} = \frac{\eta_B I_e}{\eta_{Bo} I_{eo}} = \left(\frac{\tau_e}{\tau_{eo}}\right)^{\frac{1}{2}} = \left(\frac{\eta_B}{\eta_{Bo}}\right)^{\frac{1}{2}} \tag{8b}$$

These L/L_o data are thus independent of excess current effects (space charge recombination, surface leakage and possible tunnelling), as well as hole diffusion into the n-side of the function, and allow a direct measure of the change in bulk efficiency. These data were plotted in figure 7 for samples RP 55-35, RP 78-29 and RP 71-39. (This last sample was placed in an oven at higher temperature (250^oC) and unbiased.) Note that for both biased samples L/L_o - 0.75 after the first hour of aging. The corresponding bulk efficiency ratio is $\eta_B/\eta_{No} = (L/L_o)^2 = 0.56$. This indicates that the so-called "rapid" component of aging in these LEDs is a bulk recombination effect unrelated to surface contamination which may accrue gradually in the course of aging.

The remaining factor in equation 4 is the ratio of diffusion to total diode current. This efficiency, like the injection ratio, R, can actually be enhanced during bulk degradation. Qualitatively, this enhancement may be understood as follows: As a consequence of bulk degradation,

the diffusion lengths of minority carriers are reduced, thus increasing total diffusion current at a given level of bias voltage. For diodes such as we are considering here, where rapid bulk degradation can occur, this effect can initially outstrip the increase in nondiffusion current components.

Even an approximate calculation of the injection efficiency is complicated in two respects: Accounting for the voltage dependence of nondiffusion current components as the diodes degrade and measuring the initial diffusion current. In order to obtain a reasonable estimate of injection efficiency variation, we make the following assumptions: The voltage dependence of all nondiffusion current components, throughout degradation, will be accounted for by an approximate space-charge current model:

$$I_{sc}(V) = I_{sc}^{0} e^{qV/2kT} \tag{9}$$

The assumption that this equation is valid throughout degradation, despite the evidence of figure 5, will make the calculation of η_{inj} pessimistic as degradation proceeds.

The initial diffusion current I_{do} is then taken to be the difference.

$$I_{do}(V) = I_{o}(V) - I_{sco}(V) \tag{10}$$

where $I_{o}(V)$ is the total initial measured current at V. Subscript o indicates the undegraded case. An estimate of the increase in total diffusion current requires the result obtained above that injection ratio R,

does not change significantly with degradation, i.e., the increase in hole injection is proportional to the increase in electron injection. From equations 7 and 8 it can be shown that:

$$\frac{I_d}{I_{do}} = \left(\frac{\tau_{eo}}{\tau_e}\right)^{\frac{1}{2}} = \frac{L_o}{L} \quad . \tag{11}$$

Injection efficiency may then be estimated from L-I-V data taken at various stages of degradation. Equation 9 is used to (pessimistically) extrapolate nondiffusion currents while equation 11 is used to estimate the increase in diffusion current with degradation. The result of such calculations, based on the data of figures 7 and 8, is shown in figure 15. Here we have plotted the estimate of η_{inj} vs. time at two different test currents for two different samples. Notice that the total variation of η_{inj} is less than 7% of its mean value at 10 mA for RP 55-35 and even less for RP 78-29. Even for the worst case (1 mA meas. for RP-55-35) the relative value has dropped ~20% at 1,000 hours, while the total degradation of quantum efficiency $\eta/\eta_0 \approx 0.1$. Therefore the degradation of injection efficiency is not a major factor in the degradation of these GaP LEDs, and may in fact be partly offset by an increase in injection ratio. Therefore, in addition to the experimental evidence establishing the large reduction of bulk radiative efficiency there is further data which strongly suggests that the influence of the other factors in equation 4 have minimal net effect on the degradation of external electroluminescent efficiency.

VII. SUMMARY AND CONCLUSIONS

This paper has shown detailed data on the elevated temperature degradation characteristics of red-light-emitting GaP LEDs. Analysis of the data has established these points: 1) Degradation of this material is dominated by reduction of the radiative recombination efficiency of minority carriers, 2) Other degradation modes have negligible influence over the useful operating life of the device. 3) The current dependence of degradation has been measured at ambient temperatures of $150^{o}C$ and $200^{o}C$. At a standard measurement current of 10 mA, MTTF is approximately inversely dependent on stress current ($MTTF \propto I_{stress}^{-1.13}$). When the stress and measurement currents are the same, the current dependence of degradation is weaker ($MTTF \propto I^{-.56}$).

Valuable discussions with J. S. Jayson, S. Knight, W. H. Eckton, Jr., P.D. Dapkus, R. Moest and V. G. Keramidas are gratefully acknowledged. Particular thanks are due to R. H. Saul for a critical review of the manuscript.

REFERENCES

1. J. M. Ralston and O. G. Lorimor, IEEE. Trans. Elec. Divice, ED-24, 970 (1977)
2. A. S. Jordan and J. M. Ralston, J. Appl. Phys., 47, 4518 (1976)
3. H. H. Braun, T. J. Leonard, Private communications.
4. J. J. Ralston, Rev. Sci. Instr., 43, 876 (1972)
5. W. H. Eckton, Jr., Private communication.
6. W. Rosenzweig. W. H. Hackett, Jr., and J. S. Jayson, J. Appl. Phys., 40. 4477
7. J. S. Jayson, R. Bhargava and R. W. Dixon, J. Appl. Phys., 41, 4972 (1970)
8. J. M. Ralston, J. Appl. Phys., 44 2635 (1973)
9. W. B. Joyce, et. al., J. Appl. Phys., 45, 2229 (1974)
10. R. R. Moest, Private communication.
11. J. S. Jayson, Private communication.

FIGURE CAPTIONS

Fig. 1 Relative degraded efficiency (η/η_0) as a function of time, for four groups of diodes stressed at 30 mA at a junction temperature of 220°C. Efficiency measurements were made at 10 mA.

Fig. 2 Degradation of RP 55-35 at the temperature and stress conditions indicated. The abscissa is linear in $(\text{time})^{1/2}$. The linear time scale is shown at the top of the figure.

Fig. 3 The effect of varying the current at which η/η_0 is measured, on a single group of diodes aged under the stated conditions.

Fig. 4 Degradation of groups of diodes placed in a 150° ambient and stressed at 6, 10 and 30 mA. The consequent junction temperatures are shown. All efficiency measurements (η/η_0) are at 10 mA.

Fig. 5 The L-I-V characteristics of a typical LED before and after severe degradation. Light output at fixed voltage is sharply reduced. Forward current at 1.4V is increased, but becomes less voltage dependent ($n > 2$).

Fig. 6 The dependence of absolute quantum efficiency (η) on current, before and after severe degradation. The peak in efficiency of the undegraded sample (at 3.5 mA) has all but flattened completely.

Fig. 7 Relative light measured at constant voltage (L/L_0) for three groups of LEDs. RP 55-35 and RP 78-29 were stressed at 30 mA in a 200°C ambient (T_j = 220°C), RP 71-39 was stored, unbiased, in a 250°C ambient.

Fig. 8 The growth of total device current at 1.4V. Samples and stress conditions are as indicated in the figure. At such low bias levels, the device current is totally dominated by excess current components.

Fig. 9 Arrhenius plot of elevated temperature stress data on slice RP 55-35. η/η_0 measurements at 10 mA and 30 mA are indicated. The effect of using both MTTF and τ as characteristic degradation times is shown.

Fig. 10 Arrhenius plot of elevated temperature stress data of 3 separate groups of LEDs obtained from different slices. These diodes were stressed at 30 mA. η/η_0 was determined at 10 mA.

Fig. 11 Same as Fig. 10 escept that η/η_0 was determined at 30 mA.

Fig. 12 Arrhenius plot of elevated temperature stress data on slide RP 55-35, for three different values of stress current. Note the relative insensitivity of the activation energy to stress current. τ is used as time parameter because failure has not been obtained on least-stressed samples.

Fig. 13 The dependence of characteristic failure time (τ or MTTF) on stress current. Here the data of Fig. 4 has been analyzed and corrected to a junction temperature of 150°C. The dependence of characteristic failure time on stress current is approxiamtely inverse whether τ or MTTF is used.

Fig. 14 The dependence of MTTF on device stress current. This figure shows data taken at ambient temperatures of 150°C (T_j corrected to 150°C) and 200°C (T_j corrected to 200°C). Note that at both temperatures, when degradation is measured at the stress current, the current dependence of MTTF is the same.

Fig. 15 Estimated time evolution of LED injection efficiency (based on the data of Figs. 7 and 8) at two levels of measurement current.

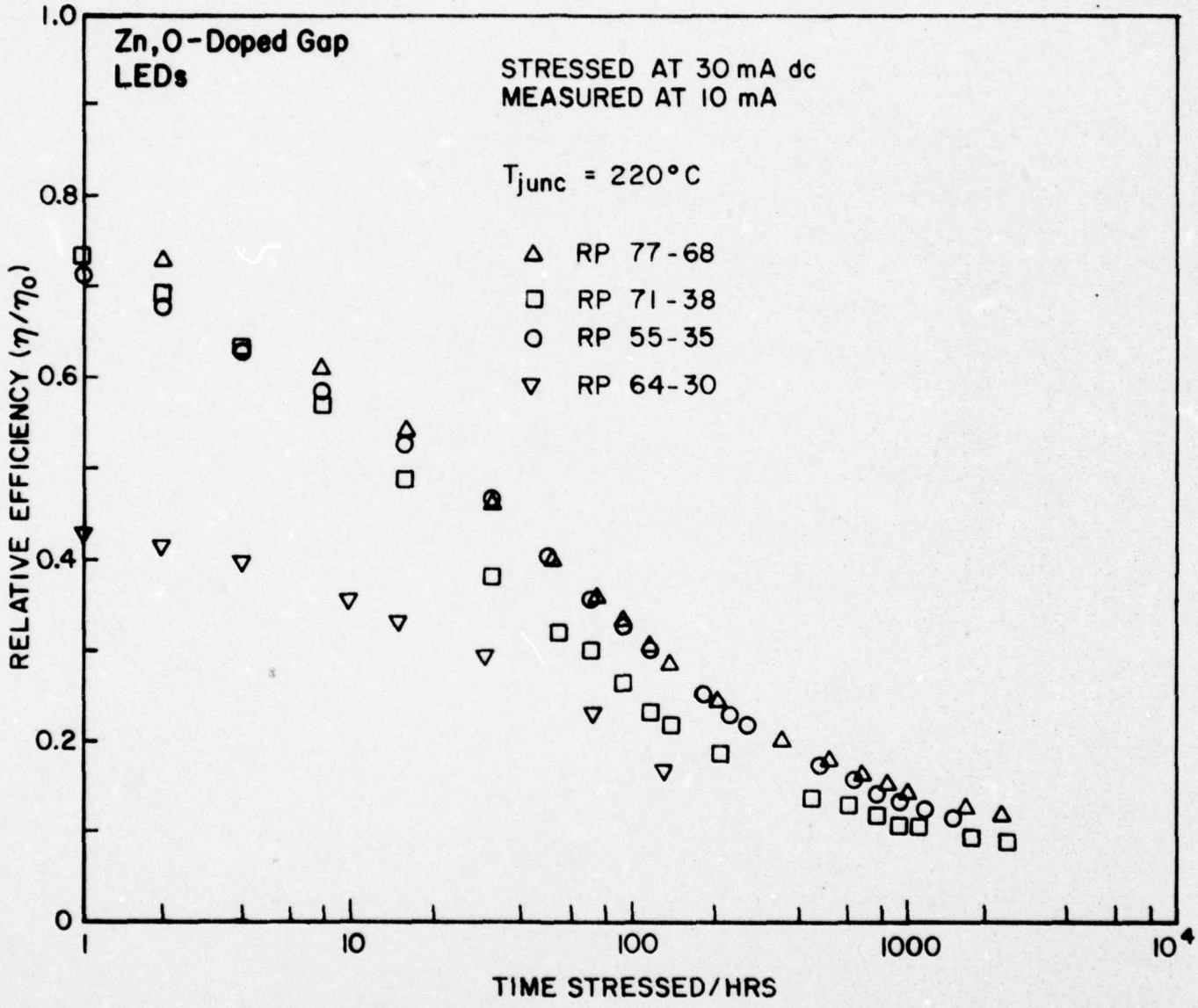

Zn,O-Doped GaP
LEDs
STRESSED AT 30 mA dc
MEASURED AT 10 mA
T_{junc} = 220°C
RP 77-68
RP 71-38
RP 55-35
RP 64-30
RELATIVE EFFICIENCY (η/η_0)
1.0
0.8
0.6
0.4
0.2
0
1
10
100
1000
10^4
TIME STRESSED/HRS

Fig. 1

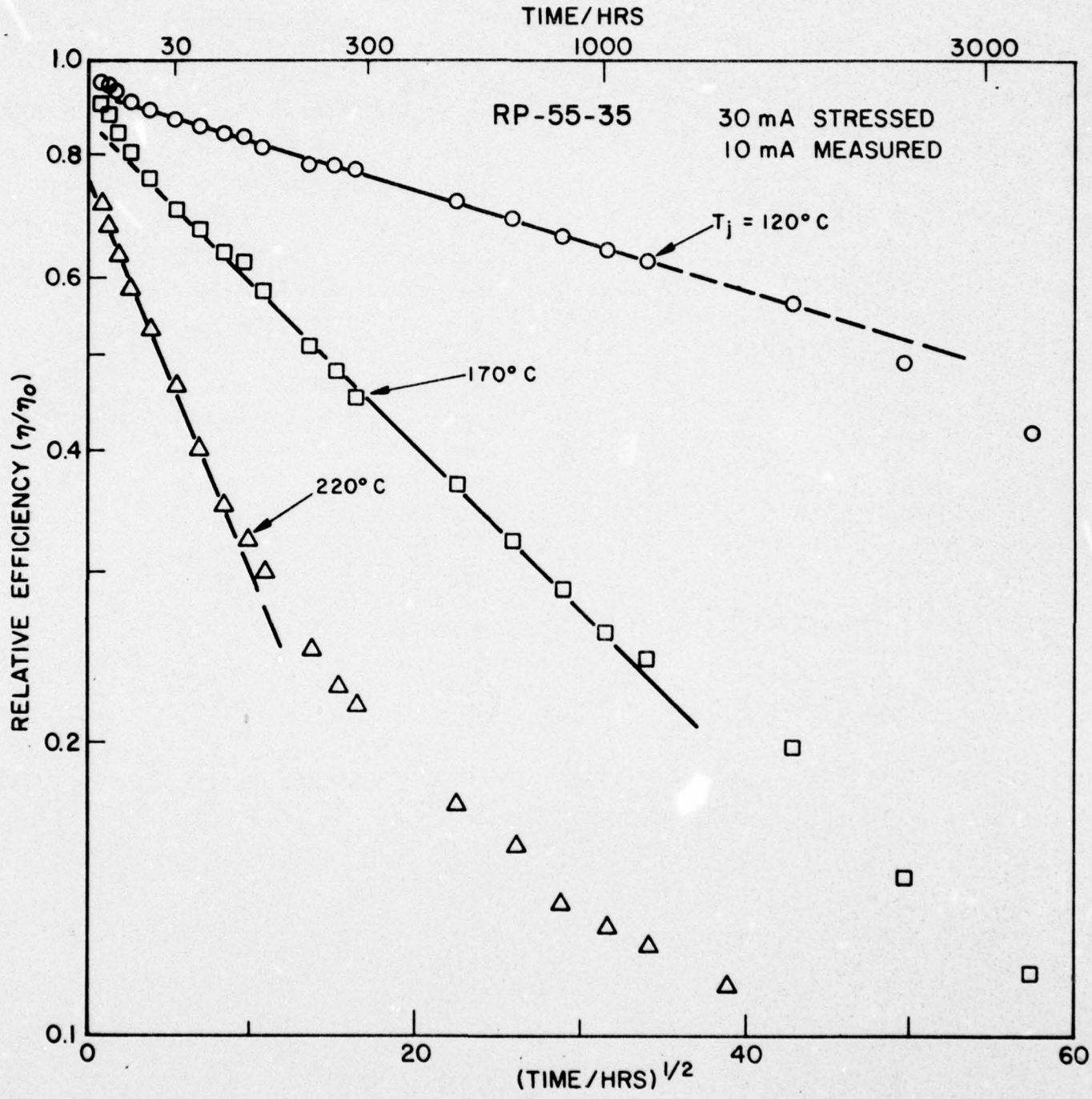

TIME/HRS
30
300
1000
3000
RP-55-35
30 mA STRESSED
10 mA MEASURED
T_j = 120° C
170° C
220° C
RELATIVE EFFICIENCY (η/η_0)
1.0
0.8
0.6
0.4
0.2
0.1
0
20
40
60
(TIME/HRS)$^{1/2}$

Fig. 2

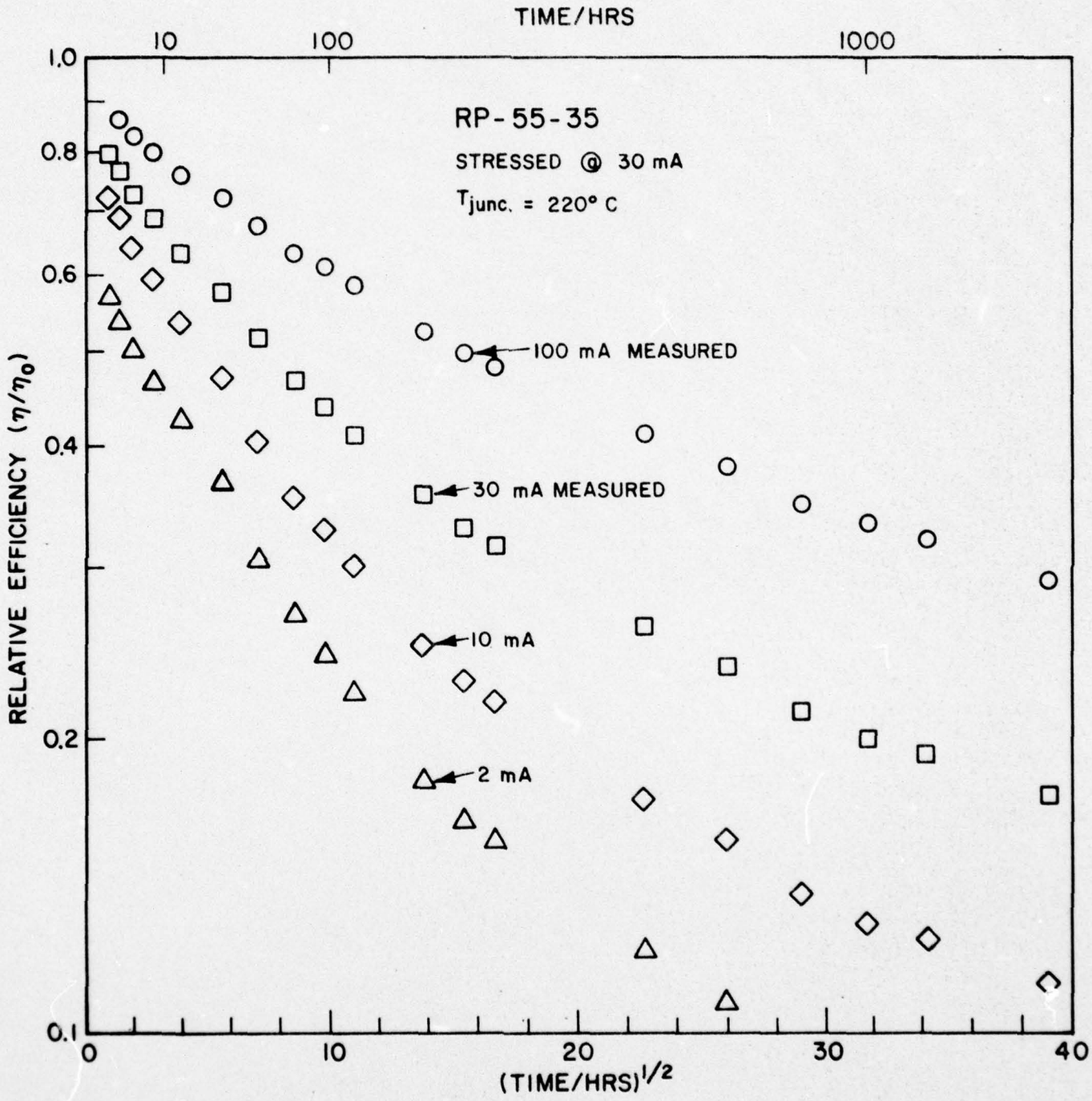

TIME/HRS
10
100
1000
RP-55-35
STRESSED @ 30 mA
$T_{junc.}$ = 220° C
100 mA MEASURED
30 mA MEASURED
10 mA
2 mA
RELATIVE EFFICIENCY (η/η_0)
1.0
0.8
0.6
0.4
0.2
0.1
0
10
20
30
40
$(TIME/HRS)^{1/2}$

Fig. 3

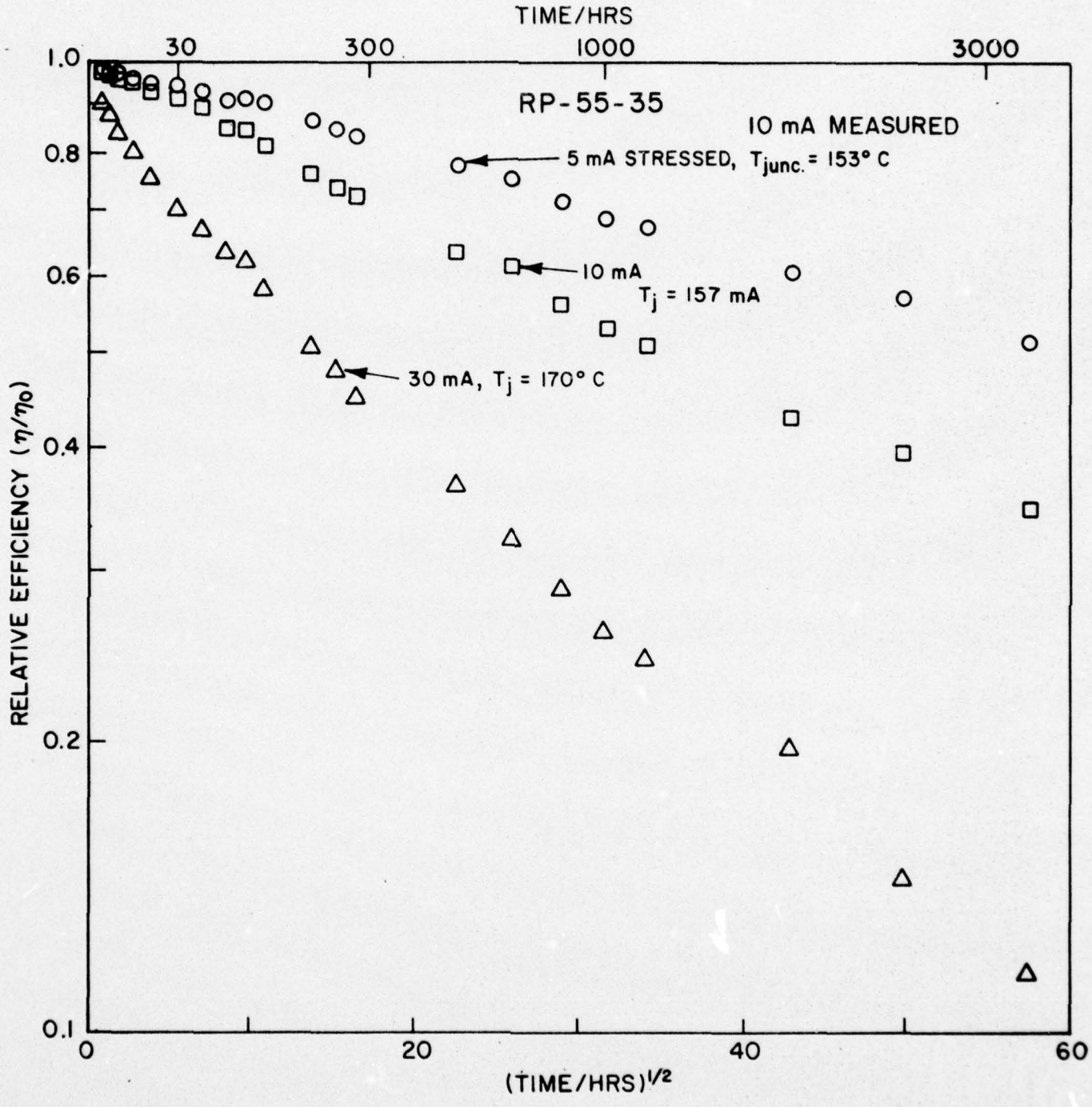

TIME/HRS
30
300
1000
3000
RP-55-35
10 mA MEASURED
5 mA STRESSED, $T_{junc.}$ = 153° C
10 mA
T_j = 157 mA
30 mA, T_j = 170° C
RELATIVE EFFICIENCY (η/η_0)
1.0
0.8
0.6
0.4
0.2
0.1
0
20
40
60
(TIME/HRS)$^{1/2}$

Fig. 4

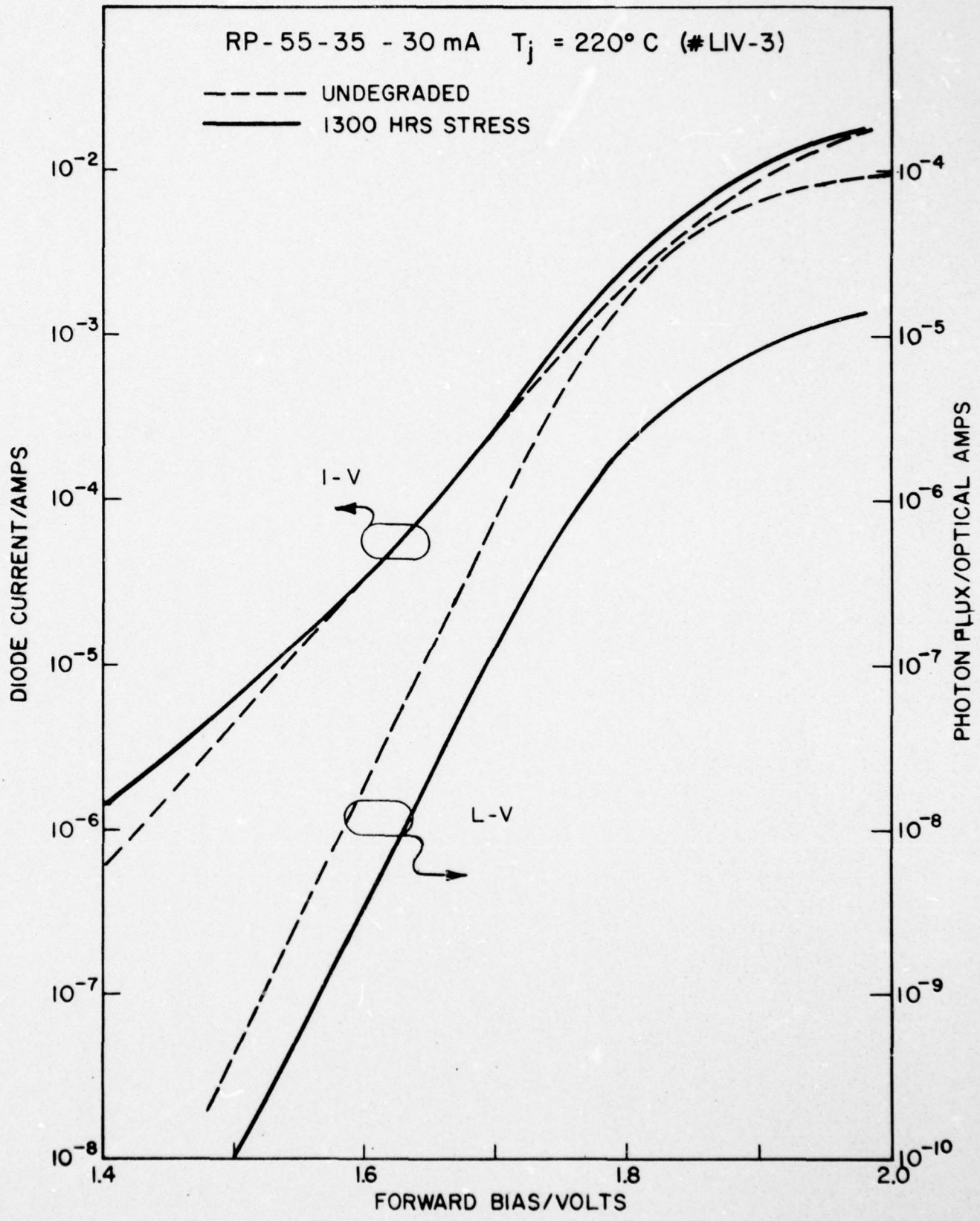

RP-55-35 - 30 mA T_j = 220° C (#LIV-3)
UNDEGRADED
1300 HRS STRESS
I-V
L-V
DIODE CURRENT/AMPS
PHOTON FLUX/OPTICAL AMPS
FORWARD BIAS/VOLTS
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1.4
1.6
1.8
2.0

Fig. 5

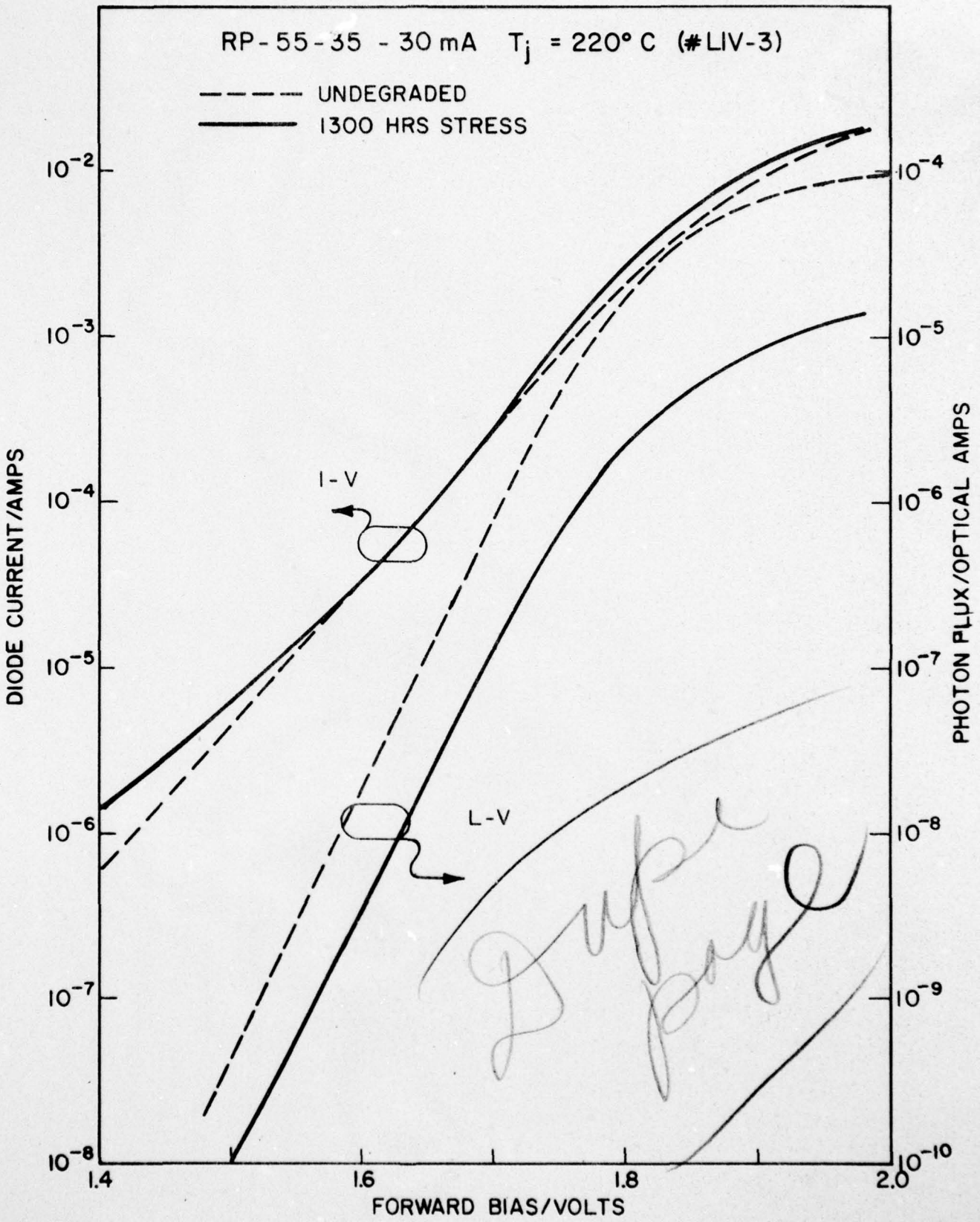

RP-55-35 - 30 mA T_j = 220° C (#LIV-3)
UNDEGRADED
1300 HRS STRESS
I-V
L-V
DIODE CURRENT/AMPS
PHOTON FLUX/OPTICAL AMPS
FORWARD BIAS/VOLTS
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1.4
1.6
1.8
2.0

Fig. 5

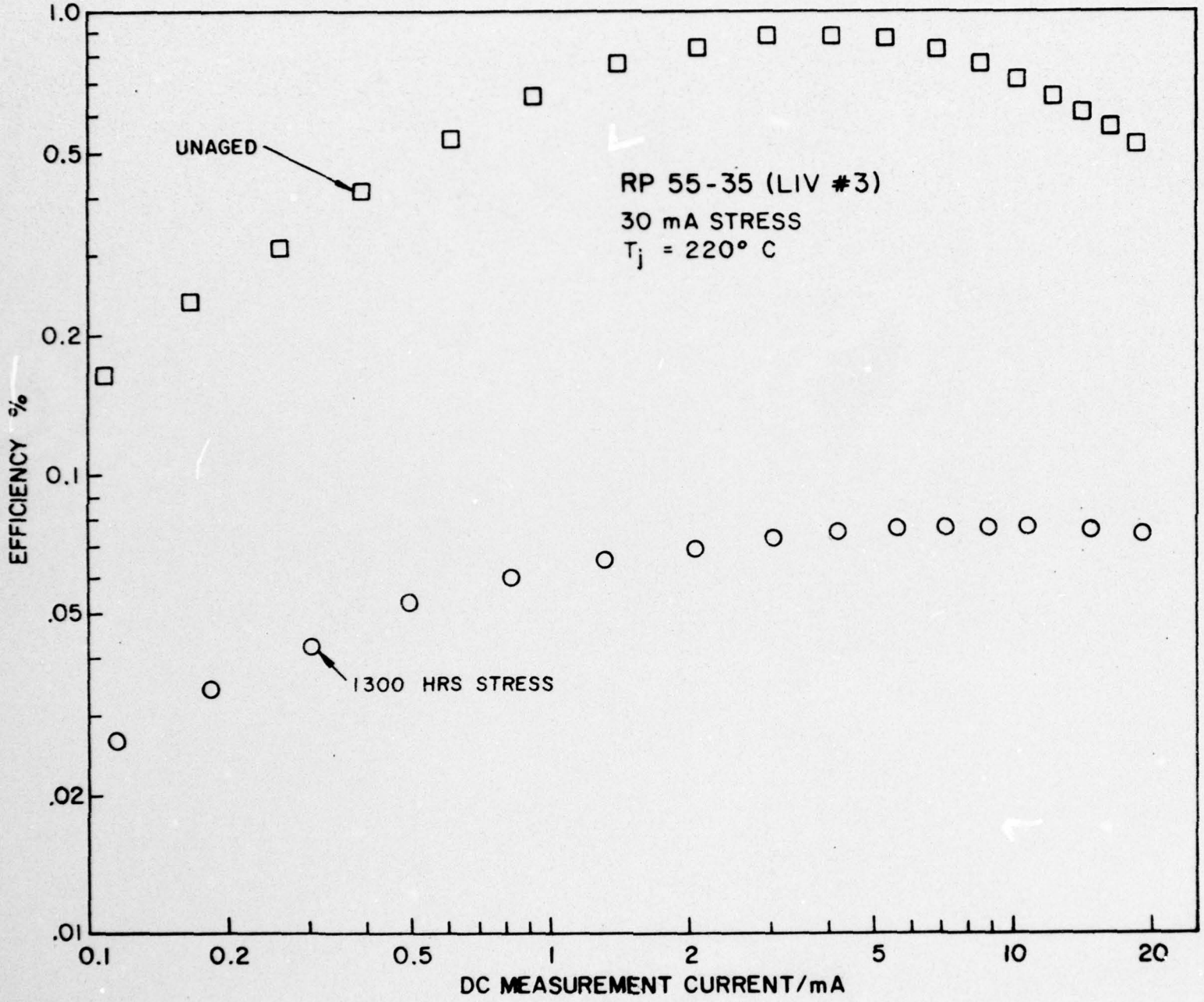

1.0
0.5
0.2
0.1
.05
.02
.01
EFFICIENCY %
UNAGED
RP 55-35 (LIV #3)
30 mA STRESS
T_j = 220° C
1300 HRS STRESS
0.1
0.2
0.5
1
2
5
10
20
DC MEASUREMENT CURRENT/mA

Fig. 6

DEGRADATION OF LIGHT OUTPUT AT FIXED VOLTAGE BIAS
L MEASURED AT 1.7V

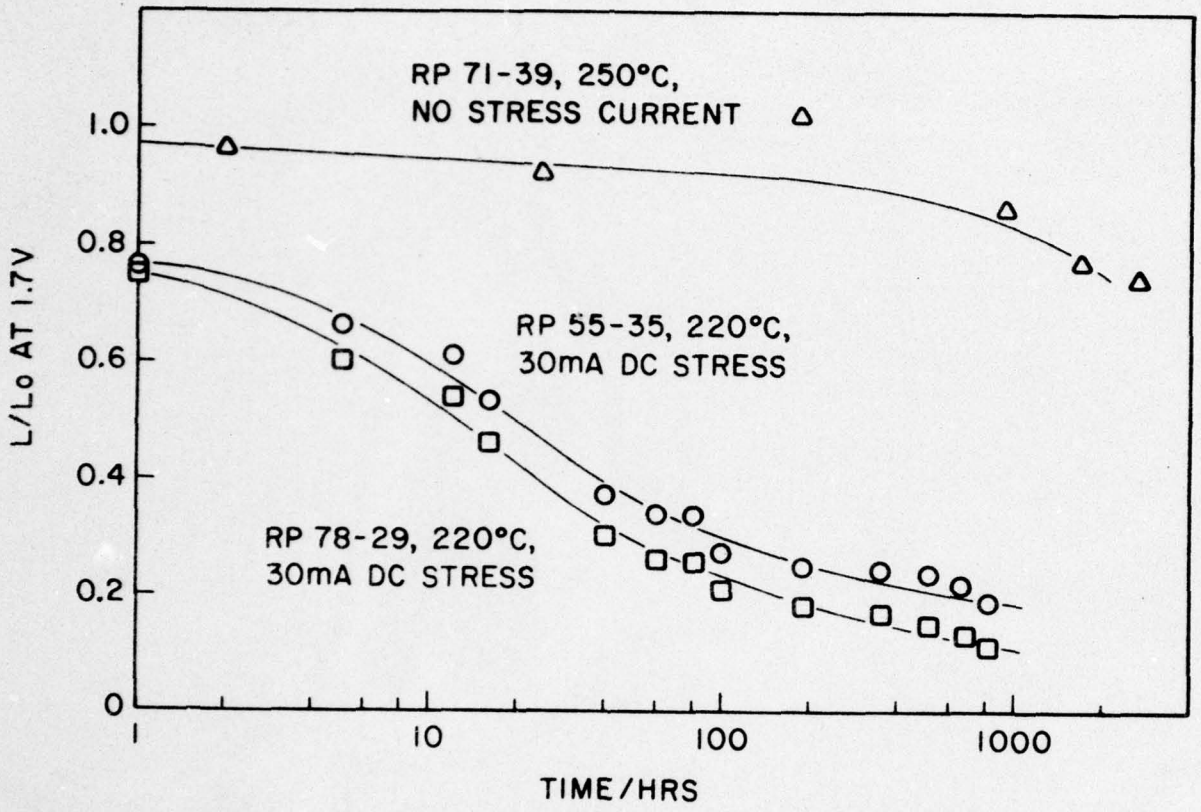


Fig. 7

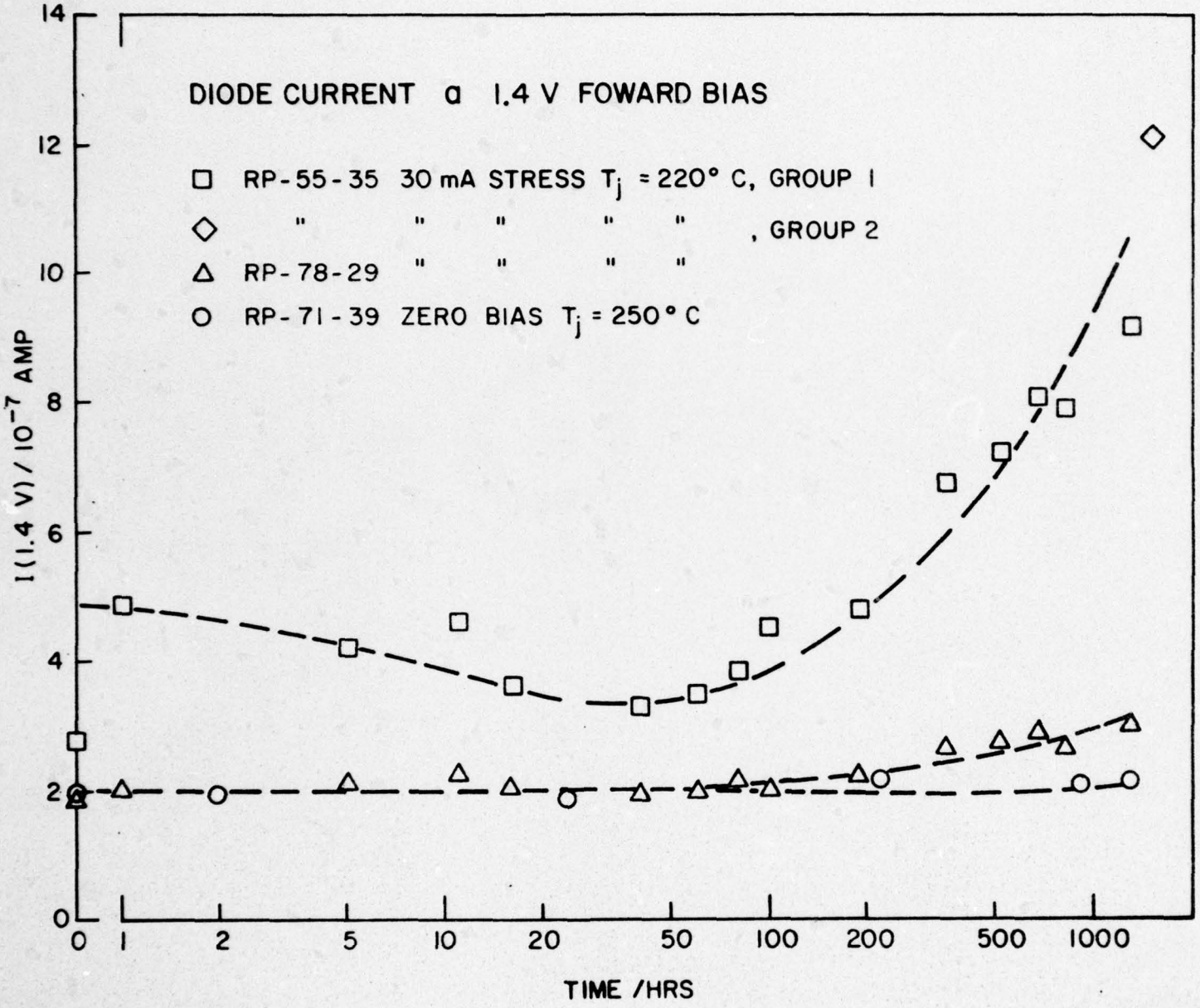

DIODE CURRENT @ 1.4 V FOWARD BIAS
RP-55-35 30 mA STRESS T_j = 220° C, GROUP 1
" " " " " , GROUP 2
RP-78-29 " " " "
RP-71-39 ZERO BIAS T_j = 250° C
I(1.4 V) / 10^{-7} AMP
0
2
4
6
8
10
12
14
0 1 2 5 10 20 50 100 200 500 1000
TIME /HRS

Fig. 8

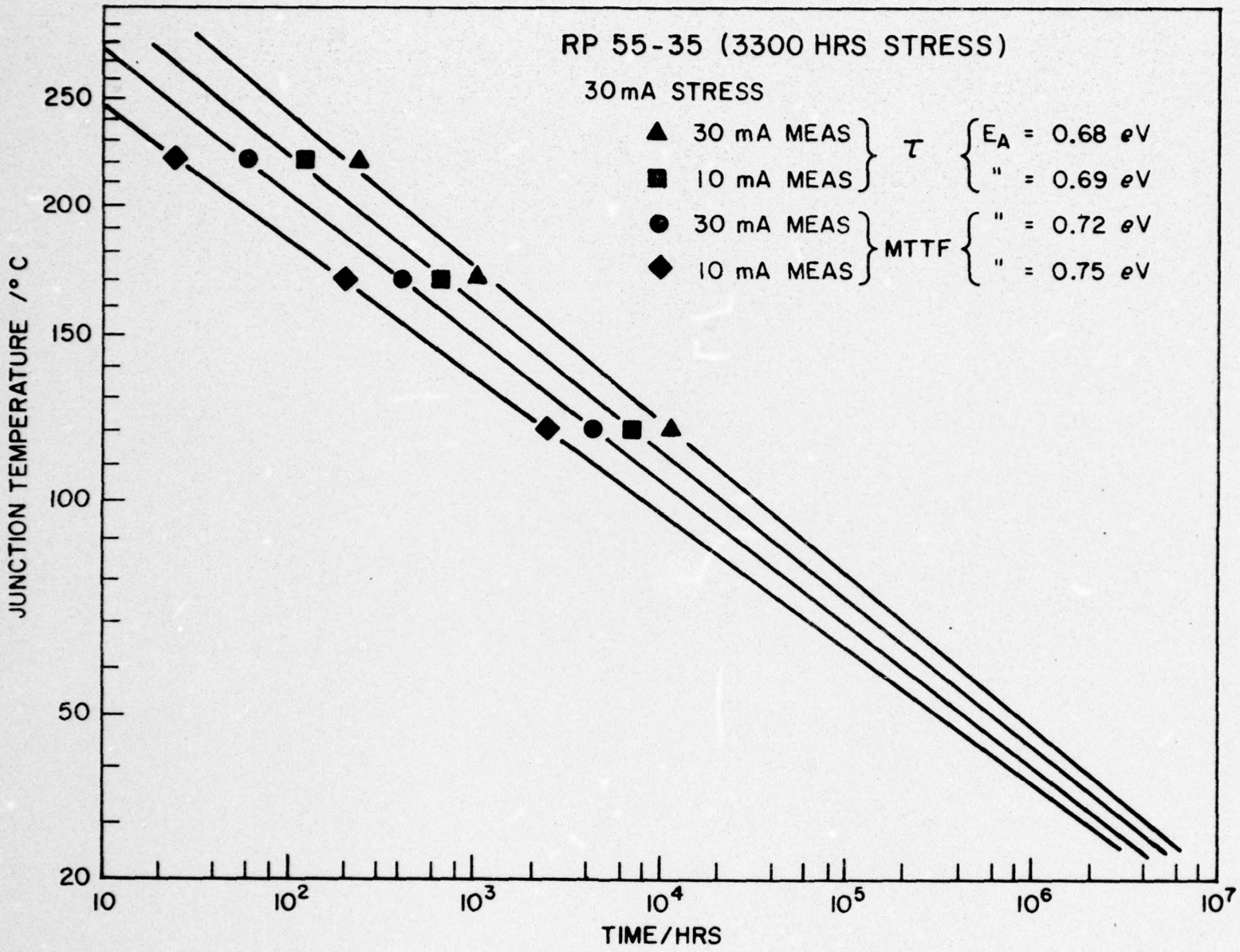

RP 55-35 (3300 HRS STRESS)
30mA STRESS
30 mA MEAS
10 mA MEAS
τ
E_A = 0.68 eV
" = 0.69 eV
30 mA MEAS
10 mA MEAS
MTTF
" = 0.72 eV
" = 0.75 eV
JUNCTION TEMPERATURE /° C
250
200
150
100
50
20
10
10^2
10^3
10^4
10^5
10^6
10^7
TIME/HRS

Fig. 9

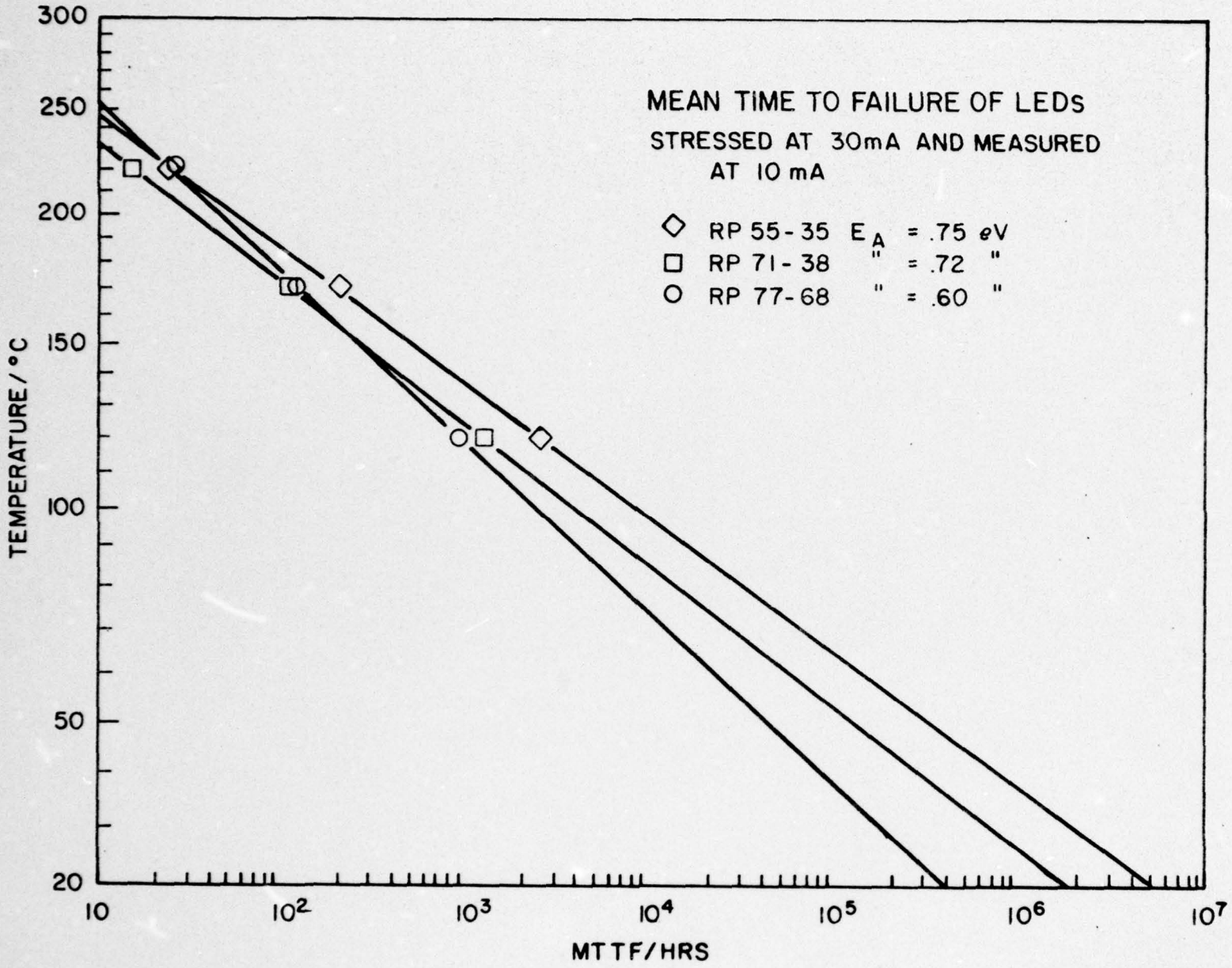

MEAN TIME TO FAILURE OF LEDs
STRESSED AT 30mA AND MEASURED AT 10 mA
◇ RP 55-35 E_A = .75 eV
□ RP 71-38 " = .72 "
○ RP 77-68 " = .60 "
TEMPERATURE / °C
300
250
200
150
100
50
20
10
10^2
10^3
10^4
10^5
10^6
10^7
MTTF/HRS

Fig. 10

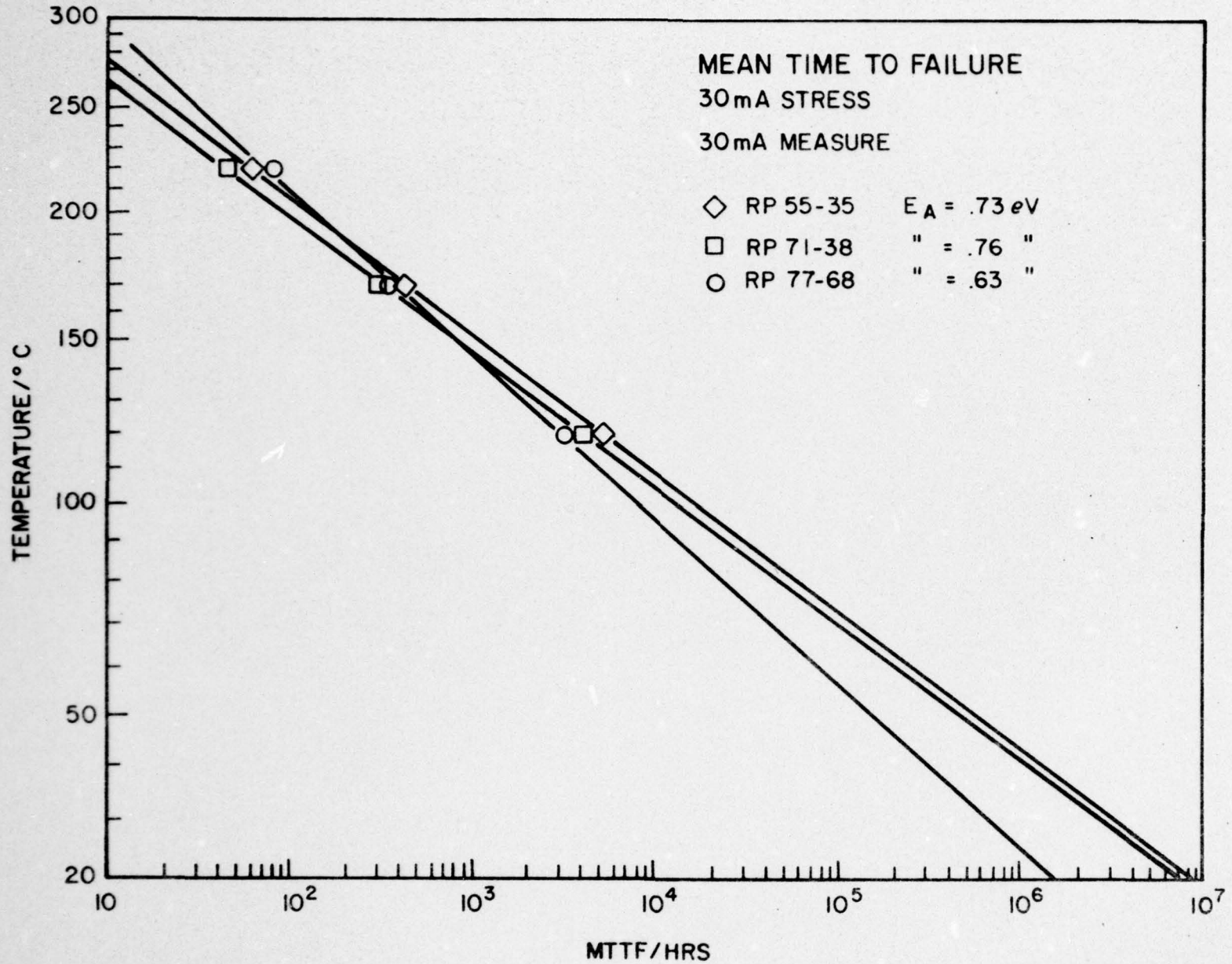

MEAN TIME TO FAILURE
30mA STRESS
30mA MEASURE
◇ RP 55-35 E_A = .73 eV
□ RP 71-38 " = .76 "
○ RP 77-68 " = .63 "
TEMPERATURE/°C
300
250
200
150
100
50
20
10
10^2
10^3
10^4
10^5
10^6
10^7
MTTF/HRS

Fig. 11

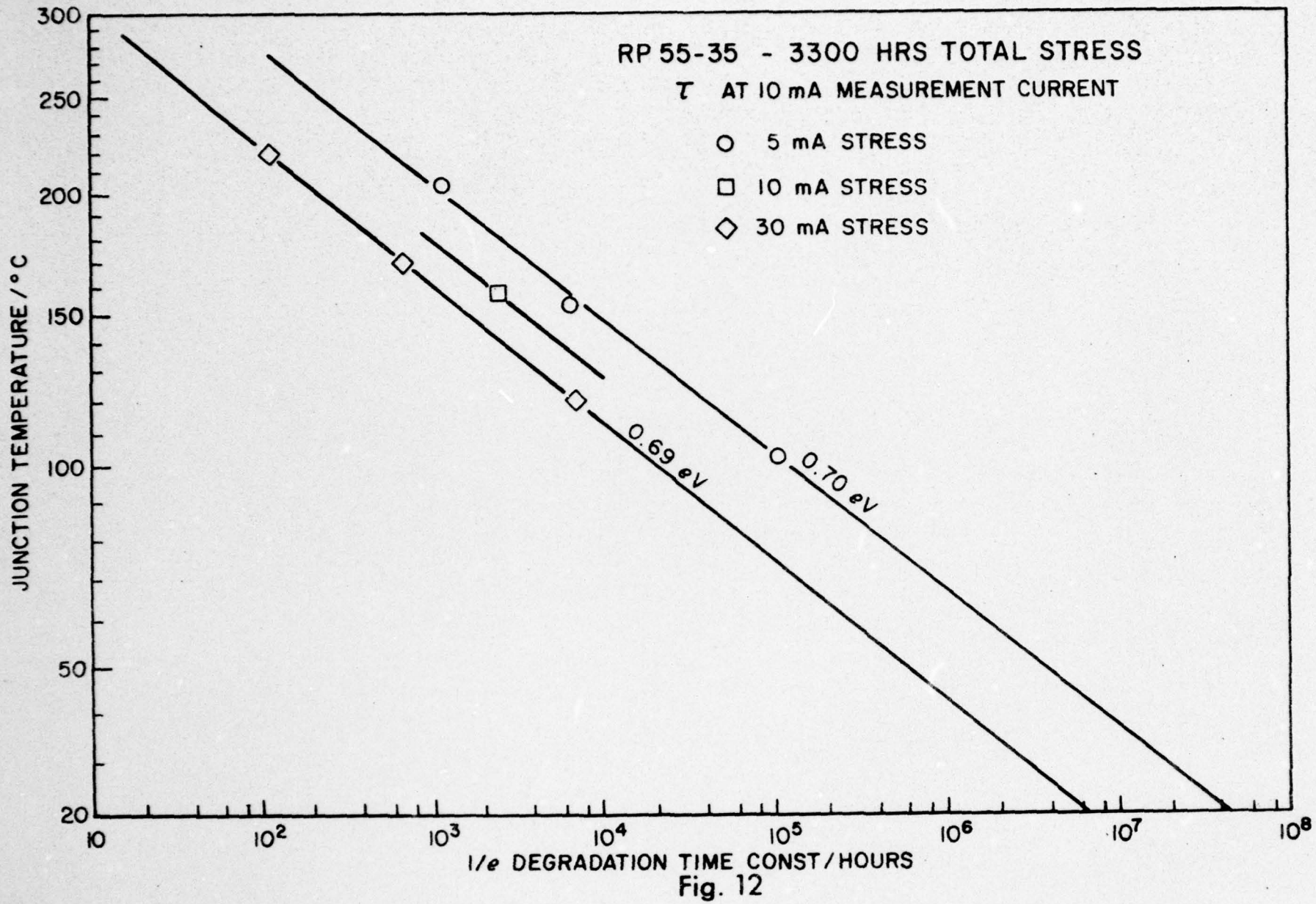

RP 55-35 - 3300 HRS TOTAL STRESS
τ AT 10 mA MEASUREMENT CURRENT
5 mA STRESS
10 mA STRESS
30 mA STRESS
0.69 eV
0.70 eV
JUNCTION TEMPERATURE / °C
300
250
200
150
100
50
20
10
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
1/e DEGRADATION TIME CONST / HOURS

Fig. 12

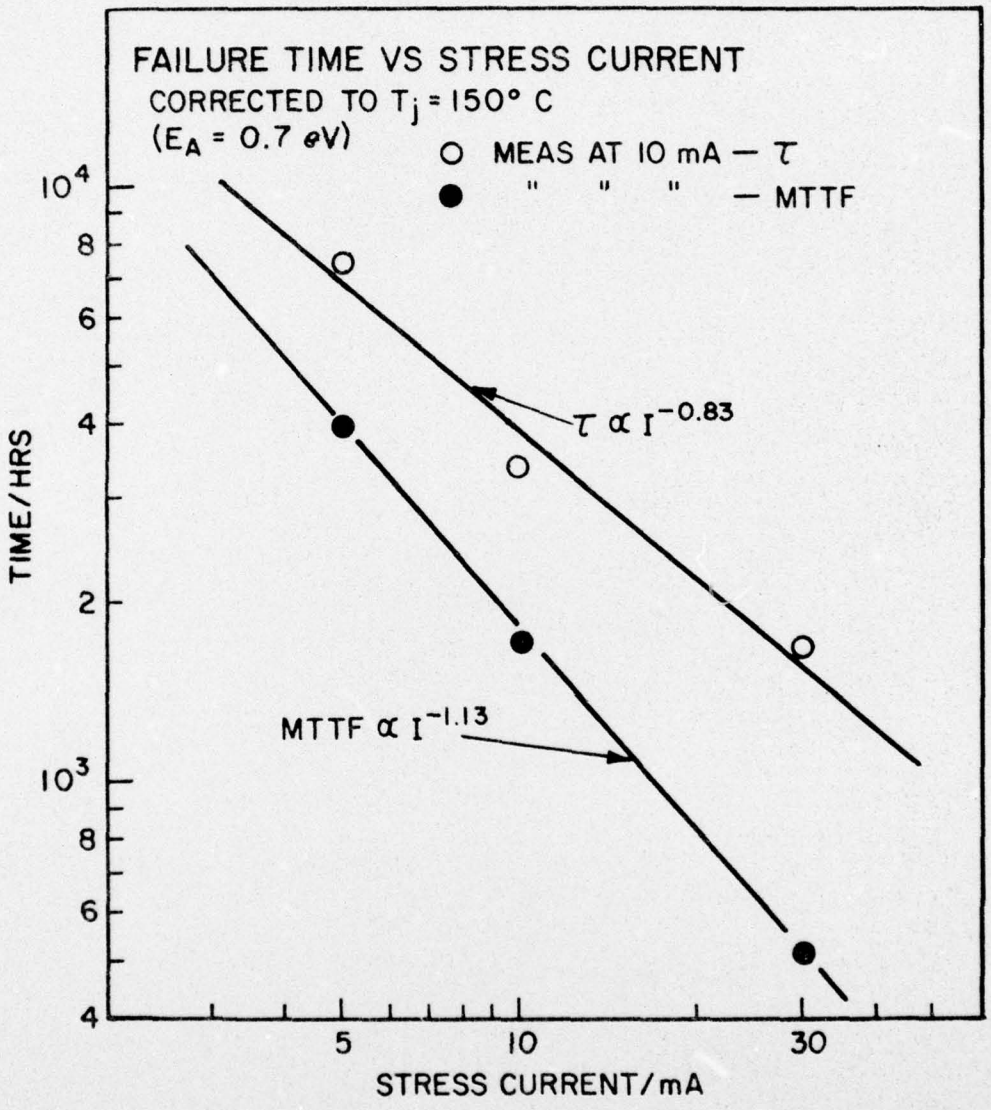

FAILURE TIME VS STRESS CURRENT
CORRECTED TO T_j = 150° C
(E_A = 0.7 eV)
O MEAS AT 10 mA — τ
● " " " — MTTF
$\tau \propto I^{-0.83}$
$MTTF \propto I^{-1.13}$
TIME/HRS
10^4
8
6
4
2
10^3
8
6
4
5
10
30
STRESS CURRENT/mA

Fig. 13

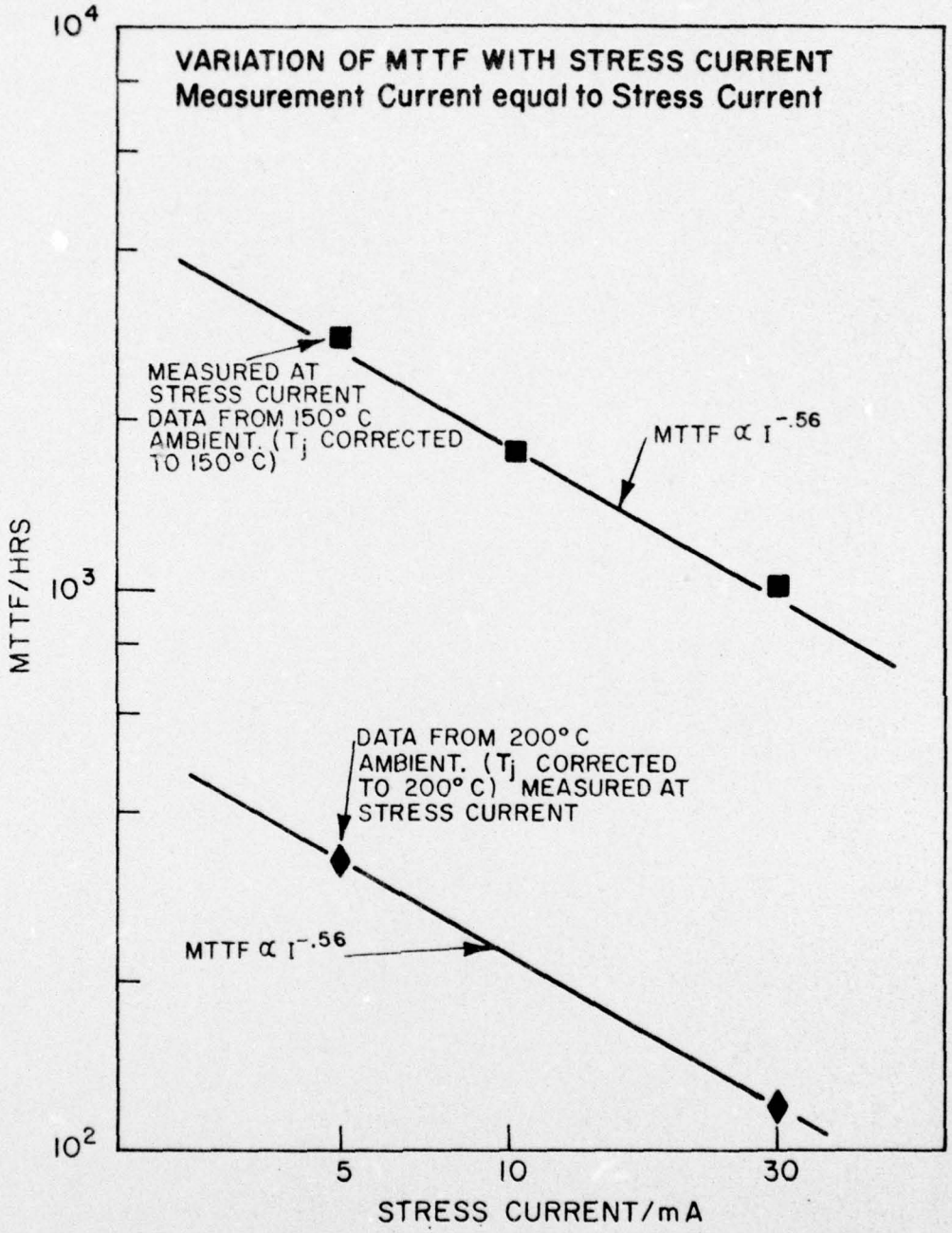

VARIATION OF MTTF WITH STRESS CURRENT
Measurement Current equal to Stress Current
MEASURED AT STRESS CURRENT DATA FROM 150° C AMBIENT. (T_j CORRECTED TO 150° C)
MTTF ∝ I$^{-.56}$
DATA FROM 200° C AMBIENT. (T_j CORRECTED TO 200° C) MEASURED AT STRESS CURRENT
MTTF ∝ I$^{-.56}$
MTTF/HRS
10^4
10^3
10^2
5
10
30
STRESS CURRENT/mA

Fig.14

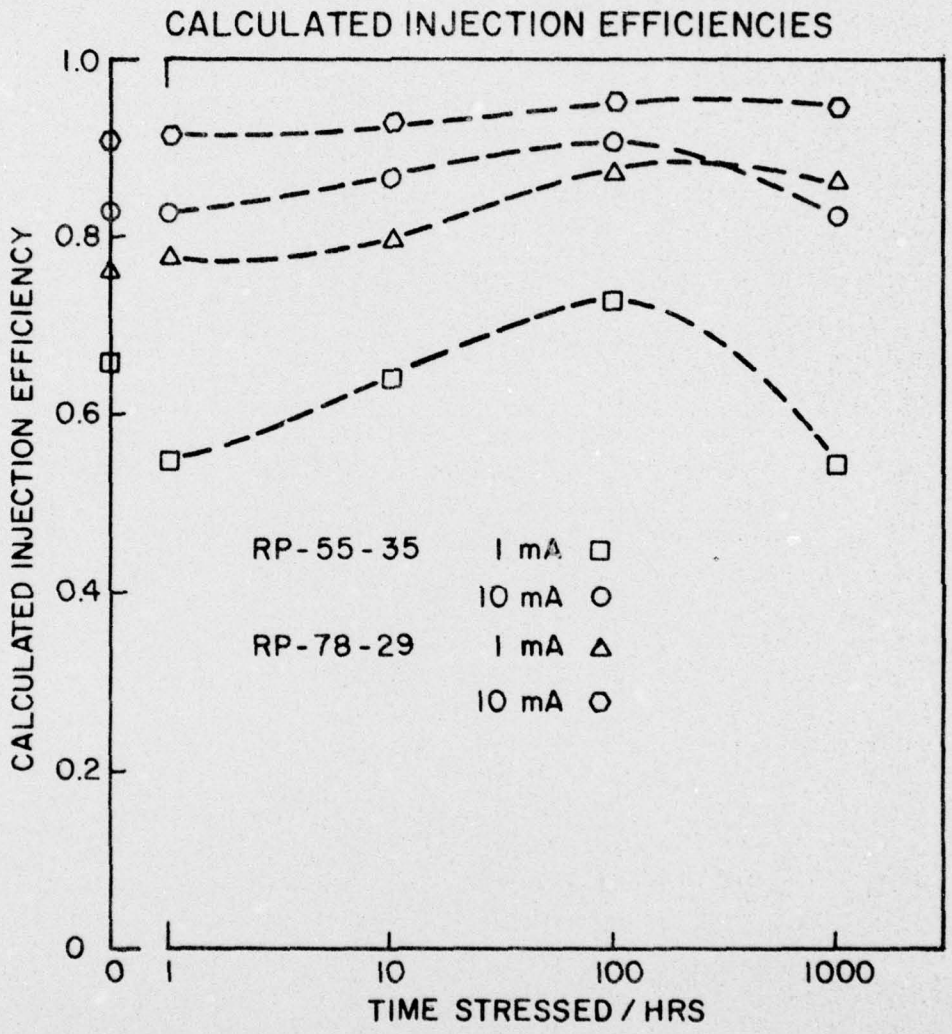

CALCULATED INJECTION EFFICIENCIES
CALCULATED INJECTION EFFICIENCY
1.0
0.8
0.6
0.4
0.2
0
0
1
10
100
1000
TIME STRESSED / HRS
RP-55-35
1 mA
10 mA
RP-78-29
1 mA
10 mA

Fig. 15

CNA Professional Papers – 1973 to Present*

PP 103
Friedheim, Robert L., "Political Aspects of Ocean Ecology" 48 pp., Feb 1973, published in Who Protects the Oceans, John Lawrence Hargrove (ed.) (St. Paul: West Publ'g. Co., 1974), published by the American Society of International Law) AD 757 936

PP 104
Schick, Jack M., "A Review of James Cable, Gunboat Diplomacy Political Applications of Limited Naval Forces," 5 pp., Feb 1973, (Reviewed in the American Political Science Review, Vol. LXVI, Dec 1972)

PP 105
Corn, Robert J. and Phillips, Gary R., "On Optimal Correction of Gunfire Errors," 22 pp., Mar 1973, AD 761 674

PP 106
Stoloff, Peter H., "User's Guide for Generalized Factor Analysis Program (FACTAN)," 35 pp., Feb 1973, (Includes an addendum published Aug 1974) AD 758 824

PP 107
Stoloff, Peter H., "Relating Factor Analytically Derived Measures to Exogenous Variables," 17 pp., Mar 1973, AD 758 820

PP 108
McConnell, James M. and Kelly, Anne M., "Superpower Naval Diplomacy in the Indo-Pakistani Crisis," 14 pp., 5 Feb 1973, (Published, with revisions, in Survival, Nov/Dec 1973) AD 761 675

PP 109
Berghoefer, Fred G., "Salaries–A Framework for the Study of Trend," 8 pp., Dec 1973, (Published in Review of Income and Wealth, Series 18, No. 4, Dec 1972)

PP 110
Augusta, Joseph, "A Critique of Cost Analysis," 9 pp., Jul 1973, AD 766 376

PP 111
Herrick, Robert W., "The USSR's 'Blue Belt of Defense' Concept: A Unified Military Plan for Defense Against Seaborne Nuclear Attack by Strike Carriers and Polaris/Poseidon SSBNs," 18 pp., May 1973, AD 766 375

PP 112
Ginsberg, Lawrence H., "ELF Atmosphere Noise Level Statistics for Project SANGUINE," 29 pp., Apr 1974, AD 786 969

PP 113
Ginsberg, Lawrence H., "Propagation Anomalies During Project SANGUINE Experiments," 5 pp., Apr 1974, AD 786 968

PP 114
Maloney, Arthur P., "Job Satisfaction and Job Turnover," 41 pp., Jul 1973, AD 768 410

PP 115
Silverman, Lester P., "The Determinants of Emergency and Elective Admissions to Hospitals," 145 pp., 18 Jul 1973, AD 766 377

PP 116
Rehm, Allan S., "An Assessment of Military Operations Research in the USSR," 19 pp., Sep 1973, (Reprinted from Proceedings, 30th Military Operations Research Symposium (U), Secret Dec 1972) AD 770 116

PP 117
McWhite, Peter B. and Ratliff, H. Donald,* "Defending a Logistics System Under Mining Attack,"** 24 pp., Aug 1976 (to be submitted for publication in Naval Research Logistics Quarterly), presented at 44th National Meeting, Operations Research Society of America, November 1973, AD A030 454
*University of Florida.
***Research supported in part under Office of Naval Research Contract N00014-68-0273-0017*

PP 118
Barfoot, C. Bernard, "Markov Duels," 18 pp., Apr 1973, (Reprinted from Operations Research, Vol. 22, No. 2, Mar-Apr 1974)

PP 119
Stoloff, Peter and Lockman, Robert F., "Development of Navy Human Relations Questionnaire," 2 pp., May 1974, (Published in American Psychological Association Proceedings, 81st Annual Convention, 1973) AD 779 240

PP 120
Smith, Michael W. and Schrimper, Ronald A.,* "Economic Analysis of the Intracity Dispersion of Criminal Activity," 30 pp., Jun 1974, (Presented at the Econometric Society Meetings, 30 Dec 1973) AD 780 538
Economics, North Carolina State University.

PP 121
Devine, Eugene J., "Procurement and Retention of Navy Physicians," 21 pp., Jun 1974, (Presented at the 49th Annual Conference, Western Economic Association, Las Vegas, Nev., 10 Jun 1974) AD 780 539

PP 122
Kelly, Anne M., "The Soviet Naval Presence During the Iraq-Kuwaiti Border Dispute: March-April 1973," 34 pp., Jun 1974, (Published in Soviet Naval Policy, ed. Michael MccGwire; New York: Praeger) AD 780 592

PP 123
Petersen, Charles C., "The Soviet Port-Clearing Operation in Bangladash, March 1972-December 1973," 35 pp., Jun 1974, (Published in Michael MccGwire, et al. (eds) Soviet Naval Policy: Objectives and Constraints, (New York: Praeger Publishers, 1974) AD 780 540

PP 124
Friedheim, Robert L. and Jehn, Mary E., "Anticipating Soviet Behavior at the Third U.N. Law of the Sea Conference: USSR Positions and Dilemmas," 37 pp., 10 Apr 1974, (Published in Soviet Naval Policy, ed. Michael MccGwire; New York: Praeger) AD 783 701

PP 125
Weinland, Robert G., "Soviet Naval Operations–Ten Years of Change," 17 pp., Aug 1974, (Published in Soviet Naval Policy, ed. Michael MccGwire; New York: Praeger) AD 783 962

PP 126 – Classified.

PP 127
Dragnich, George S., "The Soviet Union's Quest for Access to Naval Facilities in Egypt Prior to the June War of 1967," 64 pp., Jul 1974, AD 786 318

PP 128
Stoloff, Peter and Lockman, Robert F., "Evaluation of Naval Officer Performance," 11 pp., (Presented at the 82nd Annual Convention of the American Psychological Association, 1974) Aug 1974, AD 784 012

PP 129
Holen, Arlene and Horowitz, Stanley, "Partial Unemployment Insurance Benefits and the Extent of Partial Unemployment," 4 pp., Aug 1974, (Published in the Journal of Human Resources, Vol. IX, No. 3, Summer 1974) AD 784 010

PP 130
Dismukes, Bradford, "Roles and Missions of Soviet Naval General Purpose Forces in Wartime: Pro-SSBN Operation," 20 pp., Aug 1974, AD 786 320

PP 131
Weinland, Robert G., "Analysis of Gorshkov's *Navies in War and Peace*," 45 pp., Aug 1974, (Published in Soviet Naval Policy, ed. Michael MccGwire; New York: Praeger) AD 786 319

PP 132
Kleinman, Samuel D., "Racial Differences in Hours Worked in the Market: A Preliminary Report," 77 pp., Feb 1975, (Paper read on 26 Oct 1974 at Eastern Economic Association Convention in Albany, N.Y.) AD A 005 517

PP 133
Squires, Michael L., "A Stochastic Model of Regime Change in Latin America," 42 pp., Feb 1975, AD A 007 912

PP 134
Root, R. M. and Cunniff, P. F.,* "A Study of the Shock Spectrum of a Two-Degree-of-Freedom Nonlinear Vibratory System," 39 pp., Dec 1975, (Published in the condensed version of The Journal of the Acoustic Society, Vol 60, No. 6, Dec 1976, pp. 1314
Department of Mechanical Engineering, University of Maryland.

PP 135
Goudreau, Kenneth A.; Kuzmack, Richard A.; Wiedemann, Karen, "Analysis of Closure Alternatives for Naval Stations and Naval Air Stations," 47 pp., 3 Jun 1975 (Reprinted from "Hearing before the Subcommittee on Military Construction of the Committee on Armed Service," U.S. Senate, 93rd Congress, 1st Session, Part 2, 22 Jun 1973)

PP 136
Stallings, William, "Cybernetics and Behavior Therapy," 13 pp., Jun 1975

PP 137
Petersen, Charles C., "The Soviet Union and the Reopening of the Suez Canal: Mineclearing Operations in the Gulf of Suez," 30 pp., Aug 1975, AD A 015 376

***CNA Professional Papers with an AD number may be obtained from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22151. Other papers are available from the author at the Center for Naval Analyses, 1401 Wilson Boulevard, Arlington, Virginia 22209.**

PP 138
Stallings, William, "BRIDGE: An Interactive Dialogue Generation Facility," 5 pp., Aug 1975 (Reprinted from IEEE Transactions on Systems, Man, and Cybernetics, Vol. 5, No. 3, May 1975)

PP 139
Morgan, William F., Jr., "Beyond Folklore and Fables in Forestry to Positive Economics," 14 pp., (Presented at Southern Economic Association Meetings November, 1974) Aug 1975, AD A 015 293

PP 140
Mahoney, Robert and Druckman, Daniel*, "Simulation, Experimentation, and Context," 36 pp., 1 Sep 1975, (Published in Simulation & Games, Vol. 6, No. 3, Sep 1975)
*Mathematica, Inc.

PP 141
Mizrahi, Maurice M., "Generalized Hermite Polynomials,"* 5 pp., Feb 1976 (Reprinted from the Journal of Computational and Applied Mathematics, Vol. 1, No. 4 (1975), 273-277).
*Research supported by the National Science Foundation

PP 142
Lockman, Robert F., John, Christopher, and Shughart, William F. II, "Models for Estimating Premature Losses and Recruiting District Performance," 36 pp., Dec 1975 (Presented at the RAND Conference on Defense Manpower, Feb 1976; to be published in the conference proceedings) AD A 020 443

PP 143
Horowitz, Stanley and Sherman, Allan (LCdr., USN), "Maintenance Personnel Effectiveness in the Navy," 33 pp., Jan 1976 (Presented at the RAND Conference on Defense Manpower, Feb 1976; to be published in the conference proceedings) AD A021 581

PP 144
Durch, William J., "The Navy of the Republic of China – History, Problems, and Prospects," 66 pp., Aug 1976 (To be published in "A Guide to Asiatic Fleets," ed. by Barry M. Blechman; Naval Institute Press) AD A030 460

PP 145
Kelly, Anne M., "Port Visits and the "Internationalist Mission" of the Soviet Navy," 36 pp., Apr 1976 AD A023 436

PP 146
Palmour, Vernon E., "Alternatives for Increasing Access to Scientific Journals," 6 pp., Apr 1975 (Presented at the 1975 IEEE Conference on Scientific Journals, Cherry Hill, N.C., Apr 28-30; published in IEEE Transactions on Professional Communication, Vol. PC-18, No. 3, Sep 1975) AD A021 798

PP 147
Kessler, J. Christian, "Legal Issues in Protecting Offshore Structures," 33 pp., Jun 1976 (Prepared under task order N00014-68-A-0091-0023 for ONR) AD A028 389

PP 148
McConnell, James M., "Military-Political Tasks of the Soviet Navy in War and Peace," 62 pp., Dec 1975 (Published in Soviet Oceans Development Study of Senate Commerce Committee October 1976) AD A022 590

PP 149
Squires, Michael L., "Counterforce Effectiveness: A Comparison of the Tsipis "K" Measure and a Computer Simulation," 24 pp., Mar 1976 (Presented at the International Study Association Meetings, 27 Feb 1976) AD A022 591

PP 150
Kelly, Anne M. and Petersen, Charles, "Recent Changes in Soviet Naval Policy: Prospects for Arms Limitations in the Mediterranean and Indian Ocean," 28 pp., Apr 1976, AD A 023 723

PP 151
Horowitz, Stanley A., "The Economic Consequences of Political Philosophy," 8 pp., Apr 1976 (Reprinted from Economic Inquiry, Vol. XIV, No. 1, Mar 1976)

PP 152
Mizrahi, Maurice M., "On Path Integral Solutions of the Schrodinger Equation, Without Limiting Procedure,"* 10 pp., Apr 1976 (Reprinted from Journal of Mathematical Physics, Vol. 17, No. 4 (Apr 1976), 566-575).
*Research supported by the National Science Foundation

PP 153
Mizrahi, Maurice M., "WKB Expansions by Path Integrals, With Applications to the Anharmonic Oscillator,"* 137 pp., May 1976, AD A025 440
*Research supported by the National Science Foundation

PP 154
Mizrahi, Maurice M., "On the Semi-Classical Expansion in Quantum Mechanics for Arbitrary Hamiltonians," 19 pp., May 1976 (Published in Journal of Mathematical Physics, Vol. 18, No. 4, p. 786, Apr 1977), AD A025 441

PP 155
Squires, Michael L., "Soviet Foreign Policy and Third World Nations," 26 pp., Jun 1976 (Prepared for presentation at the Midwest Political Science Association meetings, Apr 30, 1976) AD A028 388

PP 156
Stallings, William, "Approaches to Chinese Character Recognition," 12 pp., Jun 1976 (Reprinted from Pattern Recognition (Pergamon Press), Vol. 8, pp. 87-98, 1976) AD A028 692

PP 157
Morgan, William F., "Unemployment and the Pentagon Budget: Is There Anything in the Empty Pork Barrel?" 20 pp., Aug 1976 AD A030 455

PP 158
Haskell, LCdr. Richard D. (USN), "Experimental Validation of Probability Predictions," 25 pp., Aug 1976 (Presented at the Military Operations Research Society Meeting, Fall 1976) AD A030 458

PP 159
McConnell, James M., "The Gorshkov Articles, The New Gorshkov Book and Their Relation to Policy," 93 pp., Jul 1976 (Published in *Soviet Naval Influence: Domestic and Foreign Dimensions*, ed. by M. MccGwire and J. McDonnell; New York; Praeger, 1977) AD A029 227

PP 160
Wilson, Desmond P., Jr., "The U.S. Sixth Fleet and the Conventional Defense of Europe," 50 pp., Sep 1976 (Submitted for publication in Adelphi Papers, I.I.S.S., London) AD A030 457

PP 161
Melich, Michael E. and Peet, Vice Adm. Ray (USN, Retired), "Fleet Commanders: Afloat or Ashore?" 9 pp., Aug 1976 (Reprinted from *U.S. Naval Institute Proceedings*, Jun 1976) AD A030 456

PP 162
Friedheim, Robert L., "Parliamentary Diplomacy," 106 pp. Sep 1976 AD A033 306

PP 163
Lockman, Robert F., "A Model for Predicting Recruit Losses," 9 pp., Sep 1976 (Presented at the 84th annual convention of the American Psychological Association, Washington, D.C., 4 Sep 1976) AD A030 459

PP 164
Mahoney, Robert B., Jr., "An Assessment of Public and Elite Perceptions in France, The United Kingdom, and the Federal Republic of Germany, 31 pp., Feb 1977 (Presented at Conference " Perception of the U.S. – Soviet Balance and the Political Uses of Military Power" sponsored by Director, Advanced Research Projects Agency, April 1976) AD 036 599

PP 165
Jondrow, James M. "Effects of Trade Restrictions on Imports of Steel," 67 pp., November 1976, (Delivered at ILAB Conference in Dec 1976)

PP 166
Feldman, Paul, "Impediments to the Implementation of Desirable Changes in the Regulation of Urban Public Transportation," 12 pp., Oct 1976, AD A033 322

PP 166 – Revised
Feldman, Paul, "Why It's Difficult to Change Regulation," Oct 1976

PP 167
Kleinman, Samuel, "ROTC Service Commitments: a Comment," 4 pp., Nov 1976, (To be published in *Public Choice*, Vol. XXIV, Fall 1976) AD A033 305

PP 168
Lockman, Robert F., "Revalidation of CNA Support Personnel Selection Measures," 36 pp., Nov 1976

PP 169
Jacobson, Louis S., "Earnings Losses of Workers Displaced from Manufacturing Industries," 38 pp., Nov 1976, (Delivered at ILAB Conference in Dec 1976), AD A039 809

PP 170
Brechling, Frank P., "A Time Series Analysis of Labor Turnover," Nov 1976. (Delivered at ILAB Conference in Dec 1976)

PP 171
Ralston, James M., "A Diffusion Model for GaP Red LED Degradation," 10 pp., Nov 1976, (Published in Journal of Applied Pysics, Vol. 47, pp. 4518-4527, Oct 1976)

PP 172
Classen, Kathleen P., "Unemployment Insurance and the Length of Unemployment," Dec 1976, (Presented at the University of Rochester Labor Workshop on 16 Nov 1976)

PP 173
Kleinman, Samuel D., "A Note on Racial Differences in the Added-Worker/Discouraged-Worker Controversy," 2 pp., Dec 1976, (Published in the American Economist, Vol. XX, No. 1, Spring 1976)

PP 174
Mahoney, Robert B., Jr., "A Comparison of the Brookings and International Incidents Projects," 12 pp. Feb 1977 AD 037 206

PP 175
Levine, Daniel; Stoloff, Peter and Spruill, Nancy, "Public Drug Treatment and Addict Crime," June 1976, (Published in Journal of Legal Studies, Vol. 5, No. 2)

PP 176
Felix, Wendi, "Correlates of Retention and Promotion for *USNA Graduates*," 38 pp., Mar 1977, AD A039 040

PP 177
Lockman, Robert F. and Warner, John T., "Predicting Attrition: A Test of Alternative Approaches," 33 pp. Mar 1977. (Presented at the OSD/ONR Conference on Enlisted Attrition Xerox International Training Center, Leesburg, Virginia, 4-7 April 1977), AD A039 047

PP 178
Kleinman, Samuel D., "An Evaluation of Navy Unrestricted Line Officer Accession Programs," 23 pp. April 1977, (To be presented at the NATO Conference on Manpower Planning and Organization Design, Stresa, Italy, 20 June 1977), AD A039 048

PP 179
Stoloff, Peter H. and Balut, Stephen J., "Vacate: A Model for Personnel Inventory Planning Under Changing Management Policy," 14 pp. April 1977, (Presented at the NATO Conference on Manpower Planning and Organization Design, Stresa, Italy, 20 June 1977), AD A039 049

PP 180
Horowitz, Stanley A. and Sherman, Allan, "The Characteristics of Naval Personnel and Personnel Performance," 16 pp. April 1977, (Presented at the NATO Conference on Manpower Planning and Organization Design, Stresa, Italy, 20 June 1977), AD A039 050

PP 181
Balut, Stephen J. and Stoloff, Peter, "An Inventory Planning Model for Navy Enlisted Personnel," 35 pp., May 1977, (Prepared for presentation at the Joint National Meeting of the Operations Research Society of America and The Institute for Management Science. 9 May 1977, San Francisco, California), AD A042 221

PP 182
Murray, Russell, 2nd, "The Quest for the Perfect Study o: My First 1138 Days at CNA," 57 pp., April 1977

PP 183
Kassing, David, "Changes in Soviet Naval Forces," 33 pp., November, 1976, (Published as part of Chapter 3, "General Purpose Forces: Navy and Marine Corps," in Arms, Men, and Military Budgets, Francis P. Hoeber and William Schneider, Jr. (eds.), (Crane, Russak & Company, Inc.: New York), 1977), AD A040 106

PP 184
Lockman, Robert F., "An Overview of the OSD/ONR Conference on First Term Enlisted Attrition," 22 pp., June 1977, (Presented to the 39th MORS Working Group on Manpower and Personnel Planning, Annapolis, Md., 28-30 June 1977), AD A043 618

PP 185
Kassing, David, "New Technology and Naval Forces in the South Atlantic," 22 pp. (This paper was the basis for a presentation made at the Institute for Foreign Policy Analyses, Cambridge, Mass., 28 April 1977), AD A043 619

PP 186
Mizrahi, Maurice M., "Phase Space Integrals, Without Limiting Procedure," 31 pp., May 1977, (Invited paper presented at the 1977 NATO Institute on Path Integrals and Their Application in Quantum Statistical, and Solid State Physics, Antwerp, Belgium, July 17-30, 1977) (Published in Journal of Mathematical Physics 19(1), p. 298, Jan 1978), AD A040 107

PP 187
Coile, Russell C., "Nomography for Operations Research," 35 pp., April 1977, (Presented at the Joint National Meeting of the Operations Research Society of America and The Institute for Management Services, *San Francisco, California*, 9 May 1977), AD A043 620

PP 188
Durch, William J., "Information Processing and Outcome Forecasting for Multilateral Negotiations: Testing One Approach," 53 pp., May 1977 (Prepared for presentation to the 18th Annual Convention of the International Studies Association, Chase-Park Plaza Hotel, St. Louis, Missouri, March 16-20, 1977), AD A042 222

PP 189
Coile, Russell C., "Error Detection in Computerized Information Retrieval Data Bases," July, 1977, 13 pp. Presented at the Sixth Cranfield International Conference on Mechanized Information Storage and Retrieval Systems, Cranfield Institute of Technology, Cranfield, Bedford, England, 26-29 July 1977, AD A043 580

PP 190
Mahoney, Robert B., Jr., "European Perceptions and East-West Competition," 96 pp., July 1977 (Prepared for presentation at the annual meeting of the International Studies Association, St. Louis, Mo., March, 1977), AD A043 661

PP 191
Sawyer, Ronald, "The Independent Field Assignment: One Man's View," August 1977, 25 pp.

PP 192
Holen, Arlene, "Effects of Unemployment Insurance Entitlement on Duration and Job Search Outcome," August 1977, 6 pp., (Reprinted from Industrial and Labor Relations Review, Vol., 30, No. 4, Jul 1977)

PP 193
Horowitz, Stanley A., "A Model of Unemployment Insurance and the Work Test," August 1977, 7 pp. (Reprinted from Industrial and Labor Relations Review, Vol. 30, No. 40, Jul 1977)

PP 194
Classen, Kathleen P., "The Effects of Unemployment Insurance on the Duration of Unemployment and Subsequent Earnings," August 1977, 7 pp. (Reprinted from Industrial and Labor Relations Review, Vol. 30, No. 40, Jul 1977)

PP 195
Brechling, Frank, "Unemployment Insurance Taxes and Labor Turnover: Summary of Theoretical Findings," 12 pp. (Reprinted from Industrial and Labor Relations Review, Vol. 30, No. 40, Jul 1977)

PP 196
Ralston, J. M. and Lorimor, O. G., "Degradation of Bulk Electroluminescent Efficiency in Zn, O-Doped GaP LED's," July 1977, 3 pp. (Reprinted from IEEE Transactions on Electron Devices, Vol. ED-24, No. 7, July 1977)

PP 197
Wells, Anthony R., "The Centre for Naval Analyses," 14 pp., Dec 1977, AD A049 107

PP 198
Classen, Kathleen P., "The Distributional Effects of *Unemployment Insurance*," 25 pp., Sept. 1977 (Presented at a Hoover Institution Conference on Income Distribution, Oct 7-8, 1977)

PP 199
Durch, William J., "Revolution From A F.A.R. – The Cuban Armed Forces in Africa and the Middle East," Sep 1977, 16 pp., AD A046 268

PP 200
Powers, Bruce F., "The United States Navy," 40 pp. Dec 1977. (To be published as a chapter in The U.S. War Machine by Salamander Books in England during 1978), AD A049 108

PP 201
Durch, William J., "The Cuban Military in Africa and The Middle East: From Algeria to Angola," Sep 1977, 67 pp., AD A045 675

PP 202
Feldman, Paul, "Why Regulation Doesn't Work," (Reprinted from *Technological Change* and *Welfare in the Regulated Industries and Review of Social Economy*, Vol. XXIX, March, 1971, No. 1.) Sep 1977, 8 pp.

PP 203
Feldman, Paul, "Efficiency, Distribution, and the Role of Government in a Market Economy," (Reprinted from *The Journal of Political Economy*, Vol. 79, No. 3, May/June 1971.) Sep 1977, 19 pp., AD A045 675

PP 204
Wells, Anthony R., "The 1967 June War: Soviet Naval Diplomacy and The Sixth Fleet – A Reappraisal," Oct 1977, 36 pp., AD A047 236

PP 205
Coile, Russell C., "A Bibliometric Examination of the Square Root Theory of Scientific Publication Productivity," (Presented at the annual meeting of the American Society for Information Science, Chicago, Illinios, 29 September 1977.) Oct 1977, 6 pp., AD A047 237

PP 206
McConnell, James M., "Strategy and Missions of the Soviet Navy in the Year 2000," 48 pp., Nov 1977, (Presented at a Conference on Problems of Sea Power as we Approach the 21st Century, sponsored by the American Enterprise Institute for Public Policy Research, 6 October 1977, and subsequently published in a collection of papers by the Institute), AD A047 244

PP 207
Goldberg, Lawrence, "Cost-Effectiveness of Potential Federal Policies Affecting Research & Development Expenditures in the Auto, Steel and Food Industries," 36 pp., Oct 1977, (Presented at Southern Economic Association Meetings beginning 2 November 1977)

PP 208
Roberts, Stephen S., "The Decline of the Overseas Station Fleets: The United States Asiatic Fleet and the Shanghai Crisis, 1932," 18 pp., Nov 1977, (Reprinted from The American Neptune, Vol. XXXVII., No. 3, July 1977), AD A047 245

PP 209 – Classified.

PP 210
Kessing, David, "Protecting The Fleet," 40 pp., Dec 1977 (Prepared for the American Enterprise Institute Conference on Problems of Sea Power as We Approach the 21st Century, October 6-7, 1977), AD A049 109

PP 211
Mizrahi, Maurice M., "On Approximating the Circular Coverage Function," 14 pp., Feb 1978

PP 212
Mangel, Marc, "On Singular Characteristic Initial Value Problems with Unique Solutions," 20 pp., Jun 1978 (To be submitted for publication in Journal of Mathematical Analysis and Its Applications)

PP 213
Mangel, Marc, "Fluctuations in Systems with Multiple Steady States. Application to Lanchester Equations," 12 pp., Feb 78, (Presented at the First Annual Workshop on the Information Linkage Between Applied Mathematics and Industry, Naval PG School, Feb 23-25, 1978)

PP 214
Weinland, Robert G., "A Somewhat Different View of The Optimal Naval Posture,"37 pp., Jun 1978 (Presented at the 1976 Convention of the American Political Science Association (APSA/IUS Panel on "Changing Strategic Requirements and Military Posture"), Chicago, Ill., September 2, 1976)

PP 215
Coile, Russell C., "Comments on: *Principles of Information Retrieval* by Manfred Kochen, 10 pp., Mar 78, (Published as a Letter to the Editor, Journal of Documentation, Vol. 31, No. 4, pages 298-301, December 1975)

PP 216
Coile, Russell C., "Lotka's Frequency Distribution of Scientific Productivity," 18 pp., Feb 1978, (Published in the Journal of the American Society for Information Science, Vol. 28, No. 6, pp. 366-370, November 1977)

PP 217
Coile, Russell C., "Bibliometric Studies of Scientific Productivity," 17 pp., Mar 78, (Presented at the Annual meeting of the American Society for Information Science held in San Francisco, California, October 1976.)

PP 218 – Classified.

PP 219
Huntzinger, R. LaVar, "Market Analysis with Rational Expectations: Theory and Estimation," 60 pp., Apr 78 (To be submitted for publication in Journal of Econometrics)

PP 220
Maurer, Donald E., "Diagonalization by Group Matrices," 26 pp., Apr 78

PP 221
Weinland, Robert G., "Superpower Naval Diplomacy in the October 1973 Arab-Israeli War," 76 pp., Jun 1978

PP 222
Mizrahi, Maurice M., "Correspondence Rules and Path Integrals," 30 pp., Jun 1978 (Invited paper presented at the CNRS meeting on "Mathematical Problems in Feynman's Path Integrals," Marseille, France, May 22-26, 1978)

PP 223
Mangel, Marc, "Stochastic Mechanics of Molecule-Ion Molecule Reactions," 21 pp., Jun 1978 (To be submitted for publication in Journal of Mathematical Physics)

PP 224
Mangel, Marc, "Aggregation, Bifurcation, and Extinction In Exploited Animal Populations*," 48 pp., Mar 1978 (To be submitted for publication in American Naturalist)
Portions of this work were started at the Institute of Applied Mathematics and Statistics, University of British Columbia, Vancouver, B.C., Canada

PP 225
Mangel, Marc, "Oscillations, Fluctuations, and the Hopf Bifurcation*," 43 pp., Jun 1978
Portions of this work were completed at the Institute of Applied Mathematics and Statistics, University of British Columbia, Vancouver, Canada.

PP 226
Ralston, J. M. and J. W. Mann*, "Temperature and Current Dependence of Degradation in Red-Emitting GaP LEDs," 34 pp., Jun 1978

PP 227
Mangel, Marc, "Uniform Treatment of Fluctuations at Critical Points," 50 pp., May 1978 (To be submitted for publication in Journal of Statistical Physics)

PP 228
Mangel, Marc, "Relaxation at Critical Points: Deterministic and Stochastic Theory," 54 pp., Jun 1978 (To be submitted for publication in Journal of Mathematical Physics)

PP 229
Mangel, Marc, "Diffusion Theory of Reaction Rates, I: Formulation and Einstein-Smoluchowski Approximation," 50 pp., Jan 1978

PP 230
Mangel, Marc, "Diffusion Theory of Reaction Rates, II Ornstein-Uhlenbeck Approximation, 34 pp., Feb 1978